technical note

Joint Federal Aviation Administration (FAA)/ Civil Aviation Authority (CAA) Microwave Landing System (MLS) Area Navigation (RNAV) Flight Evaluations

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16. Abstract

A series of flight evaluations were conducted at Cardiff and Heathrow Airports in the United Kingdom. The flight evaluation were jointly conducted by the Kingdom of the Netherlands, the Civil Aviation Authority (CAA) of the United Kingdom, and the Federal Aviation Administration (FAA) of the United States of America. The flight evaluations were undertaken to validate recommendations made at the 13th All Weather Operations Panel (AWOP) Meeting of the International Civil Aviation Organization (ICAO). The recommendations addressed permissible Microwave Landing System (MLS) azimuth antenna offsets from the primary runway, by permissible parallel secondary runway locations, and the use of standard distance measuring equipment for computed centerline operations. In all cases, flight data validated the recommendations. Additionally, subject pilots expressed strong support for the advanced procedures they flew. Although not an objective of the evaluation, interoperability of MLS equipment manufactured in five different countries was demonstrated.

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EXECUTIVE SUMMARY

In September 1990, a series of flight evaluations of an Microwave Landing System (MLS) Area Navigation (RNAV) was conducted at Cardiff, Wales, and Heathrow Airports in the United Kingdom. The tests were jointly conducted by the National Aerospace Laboratory of the Kingdom of the Netherlands, the Civil Aviation Authority (CAA) of the United Kingdom, the Federal Aviation Administration (FAA) of the United States, the BFS of Germany, the Netherlands, Department of Civil Aviation (RLD) of the Kingdom of the Netherlands, and the United Kingdom's Ministry of Defense. The tests were conducted to evaluate recommendations made at the 13th meeting of the International Civil Aviation Organization's (ICAO) All Weather Operations Panel (AWOP).

At Montreal, AWOP made several recommendations concerning computed centerline operations. However, it was requested that flight test data be obtained to validate the recommendations. The recommendations concerned the permissible azimuth antenna offsets from the primary runway, the permissible locations of secondary parallel runways, and the use of standard distance measuring equipment (DME) for computed centerline operations. MLS equipment siting at both Cardiff and Heathrow Airports provided the opportunity to conduct the flight evaluations with equipment sited near the permissible limits identified in the AWOP 13 recommendations.

In all cases, flight data collected during these evaluations flights supported recommendations made by AWOP 13. Additionally, the interoperability of MLS airborne equipment was demonstrated by using various airborne MLS components manufactured in five different countries. Thirteen subject pilots with no experience with MLS RNAV flew the FAA Boeing 727 during the flight evaluations. All subject pilots expressed a strong desire for the adoption of the use of the advanced procedures they flew.

INTRODUCTION

BACKGROUND.

In September 1990, a series of Microwave Landing System (MLS) evaluation flights were jointly conducted by the United States' Federal Aviation Administration (FAA) and the United Kingdom's Civil Aviation Authority (CAA). These evaluation flights were designed to collected flight performance data on the use of the MLS to support advanced MLS operations. These advanced operations included an MLS area navigation (RNAV) curved path departure, an MLS computed centerline approach to a widely separated parallel runway, an MLS RNAV procedure involving a change in the vertical profile, and a computed centerline procedure which used standard distance measuring equipment (DME) rather than the precision mode DME (DME/P). Besides the CAA, other evaluation test participants included the FAA, UK's Ministry of Defense, the German BFS, the Dutch Department of Civil Aviation (RLD), and the Dutch National Aerospace Research Laboratory (NLR).

ALL WEATHER OPERATIONS PANEL (AWOP).

During the International Civil Aviation Organization (ICAO) AWOP meeting in Montreal in March 1990, several analytical results of different applications of MLS RNAV were presented (reference 1). The recommendations prepared for the Air Navigation Council contained recommendations for the inclusion of guidance material in Annex 10 on computed centerline operations. The recommendations were forwarded with the stipulation that flight evaluation should be conducted to validate the analytical results.

COMPUTED CENTERLINE OPERATIONS.

One of the major benefits of MLS is its ability to provide for precision guidance through a large volume of coverage. Through the use of an on-board computer it is possible to provide for very accurate three-dimensional RNAV within the coverage volume. Analytical results have shown the accuracy of computed lateral or vertical position to be equivalent to or better than existing Category I accuracy requirements for the Instrument Landing System (ILS). One of the most useful applications of MLS RNAV is to correct for runway alignment where the azimuth transmitter must be offset from the runway centerline due to siting constraints. Several flight tests of this application have been performed in the United States at locations such as Lebanon, New Hampshire, and Washington National Airport.

AWOP SITING GUIDELINES.

During the AWOP meeting in Montreal, siting guidelines for the maximum offset of the MLS azimuth antenna from the primary MLS runway centerline were developed. The primary runway is the runway which has its geometrical relationship to the MLS ground components identified in the MLS basic and auxiliary A data words. The guidelines were developed for cases when ranging information is provided by DME/P equipment and when ranging is provided by standard DME. Additional guidance was provided for siting limitations where MLS computed centerline operations are to be conducted to a parallel secondary

runway. A secondary runway is a runway which does not have its geometric relationship to the MLS ground equipment contained in the MLS basic and auxiliary A data words. The AWOP recommendations called for the use of computed lateral guidance for computed centerline operations to the primary runway. The recommendations noted that vertical guidance could be provided by the basic MLS elevation function. However, because of the large offsets of the elevation transmitter in the case of secondary runway applications, both lateral and vertical guidance should be computed. The AWOP recommended guidance material additions on computed centerline operations to Annex 10 are presented in appendix A.

EVALUATION OBJECTIVES.

During evaluation planning sessions conducted by the FAA and CAA it was noted that the most effective evaluation would be a flight evaluation that provided flight test data taken where the azimuth antenna was sited at or near the limits of azimuth antenna siting identified in the AWOP recommendations. The primary objective of the Joint CAA/FAA MLS RNAV evaluation was the flight verification of AWOP 13 recommendations through airborne flight data collection. This evaluation addressed the following specific topics.

1. MLS RNAV computed lateral accuracy and signal quality when conducting a computed centerline operation to the primary runway when using standard DME ranging information.

2. MLS RNAV computed lateral and vertical accuracy and signal quality when conducting a computed centerline operation to a widely separated parallel secondary runway.

3. MLS RNAV accuracy when flying a curved path departure.

4. MLS RNAV accuracy in providing vertical guidance during a two-segment glidepath procedure.

Another objective of the demonstration was the pilot acceptability of the advanced MLS procedures. The measure of acceptability was obtained through the use of pilot questionnaires administered to the pilots who participated in the flight demonstration.

MLS EQUIPMENT INTEROPERABILITY.

Although not an initial evaluation objective, the flight tests provided the opportunity to evaluate the interoperability of various pieces of MLS ground and airborne equipment manufactured in several different countries. The flight evaluation provided the chance to validate equipment standardization based on Annex 10 documentation.

SCHEDULE.

An important aspect of the flight evaluation was the minimum preparation required for the evaluation flights. Two planning sessions were held between the FAA and the CAA. These meetings were conducted at the CAA in downtown London. In June 1990, the sites for the evaluations were identified. A joint site visit was made to the two evaluation locations. At Heathrow Airport in London, an MLS is sited on runway 27R; however, a DME/P transponder was

required. This was provided by the FAA. At Cardiff, Wales, which had no MLS service, the CAA installed an MLS for the evaluation flights.

During the last week of August an FAA Boeing 727-100 aircraft, which also served as the evaluation aircraft, transported the FAA test personnel and the DME/P transponder. The aircraft arrived in Cardiff on August 26. The aircraft was based at Cardiff for the evaluation period. The transponder and antenna were shipped by ground transportation for siting at Heathrow Airport. Two days of testing and procedure refinement occurred on August 28 and 29. Between September 1-3, flight data collection were conducted at Cardiff. The flight data collection at Heathrow Airport were conducted on September 5-6 in conjunction with demonstration flights conducted for the United Kingdom aviation community.

Data collection at Cardiff and Heathrow had to be conducted during two different time periods since only one ground reference tracking system was available. Following the evaluation flight on the September 6 the Boeing 727 returned to the United States on September 8.

TEST EQUIPMENT

The FAA aircraft has been designed as a flying laboratory. The MLS RNAV guidance has been interfaced with the electromechanical cockpit displays in accordance with guidance provided in Radio Technical Commission for Aeronautics Document (RTCA DO) 198 (reference 2). In the cabin area several auxiliary displays are available to keep "passengers" informed of flight progress. The capability to reproduce in real-time flight tracks in MLS coverage also exist. Sufficient antenna coverage was obtained with only two MLS antennas on the Boeing 727.

Equipment required for support of the MLS RNAV evaluation flights consisted of a variety of airborne and ground equipment. It is noted that much of the equipment was required for data recording and display support for personnel in the cabin area of the Boeing 727. Test equipment was required to support several different evaluation functions. These functions included:

1. The radiation of basic MLS guidance by MLS ground equipment conforming to ICAO Standard and Recommended Practices (SARPS) contained in Annex 10.

2. Reception of basic MLS guidance information by certified airborne receivers.

3. MLS RNAV computations and flight guidance performed by a prototype navigation computer.

4. Control and display of real-time MLS RNAV guidance to support flight crew and engineering requirements.

5. Real-time recording of flight test data.

6. Ground tracking to collect aircraft "truth" position data.

7. On board real-time display of aircraft position on a computer generated map.

8. Remote real-time display of the cockpit attitude director indicator and horizontal situation indicator. The display was located in the cabin area.

MLS RNAV AVIONICS SUITE.

Figure 1 depicts the block diagram of the MLS RNAV avionics suite installed in the Boeing 727. The cockpit control unit was a King KDS 6800 control display unit. The software was modified to provide for display of information that was relative to MLS RNAV. The interfaces depicted are minimum interfaces required by reference 1 for a Level III MLS RNAV system. Although data were collected on the performance of three different MLS receivers, only data from the Bendix 20A MLS receiver was used for MLS RNAV. The DME/P interrogator was the Standard Electric Lorenz 400 interrogator. RNAV path storage and computation of lateral and vertical position estimates was accomplished in the MLS RNAV computer. This computer employed 32 bit processing and used a Motorola 68020 processor. All code was written in the C language and RNAV position computation was based on the Case 12 algorithm of reference 1.

An interface was developed to provide flight director roll and pitch commands when flying MLS RNAV procedures. The Boeing 727 was equipped with an FD 109 flight director and Sperry SPZ 50 flight control system. The vertical guidance channel was unmodified for presentation of vertical path flight director guidance. The elements displayed by the control and display unit are depicted in figure 2. The definition of the display fields are presented in table 1.

AIRBORNE FLIGHT DATA COLLECTION EQUIPMENT.

Figure 3 depicts the configuration of the flight data collection equipment. The same processor was used to drive the MLS RNAV system. The data collection system consisted of four major components; the MLS RNAV data collection system rack, the Hewlett-Packard (HP) printer rack, log video recording rack, and MLS receiver and DME rack.

The MLS RNAV data collection rack provided for digital recording of many MLS RNAV system parameters on 9-track magnetic tape. This rack also provided operator control of the data recording system and for real-time display of aircraft position on a computer generated video map. Additional current state information was provided to passengers in the cabin area through the use of a remote course/vertical deviation indicator, which repeated the information displayed to the cockpit crew.

The HP printer rack permitted the printing of a digital map following the completion of each RNAV procedure. This material was then given to the pilot who flew the procedure so that he could critique his own performance. The log video recording rack permitted the recording of the log video output from any of the MLS receivers. This rack also contained the Mini-Ranger C band DME transponder used to support ground tracking of the aircraft. The MLS and DME rack contained the other MLS receivers used during the evaluation.

TABLE 1. COCKPIT DISPLAY UNIT FIELD DEFINITIONS

1. 1st Line

   a. Navigation state

      3D = three-dimensional

      2D = two-dimensional

      None = No RNAV

   b. Time - Hours, minutes, seconds

   c. Recorder State Data Recording Active (DAT)

2. 2nd Line

   a. Profile - Name of the selected procedure

   b. ARM/ENG - ARM implies en route display scaling

      EMG implies ILS like display scaling

3. 3rd line AZ - Present azimuth position in degrees (xx.xx°)

4. 4th line EL - Present elevation position in degrees (x.xx°)

5. 5th line PDME - Present slant range in nautical miles (xx.xx nmi)

6. 6th line

   a. ATD - Along track distance in nmi to threshold

   b. Estimated time to threshold in minutes and seconds

7. 7th line Z - Computed height above runway datum

8. 8th line GSPD - Ground speed estimate based on MLS

9. 9th line PHI - Bias in the bank angle for lateral guidance on curved segments

10. 10th line - Numerical number of the waypoints you are preceding from/ to

11. 11th line DTW - Distance to the active waypoint in nmi with a time estimate in minutes and seconds.

12. CTE - Cross track error in degrees = Lateral FTE in degrees

13. HTE - Vertical error in degrees = Vertical FTE in degrees

14. CRS Digital display of track to the active waypoint

GROUND EQUIPMENT.

For this flight evaluation, MLS ground equipment was located at both Cardiff, Wales, and London's Heathrow Airports. The MLS ground equipment consisted of a Siemens Plessy MLS system at both locations. The azimuth and elevation beamwidths were 2.0° and 1.5°, respectively. The equipment was provided through a contract with the CAA. The DME transponder at Cardiff was a standard transponder Model 1117 manufactured by Fernau, Ltd., of the United Kingdom. This permitted evaluation of those AWOP 13 recommendations which were based on the use of a standard DME transponder. The transponder used at London Heathrow Airport was the more accurate DME/P transponder meeting ICAO Annex 10 DME/P standard 1 accuracy requirements. This transponder was provided by E-Systems, Montek Division, of Salt Lake City, Utah, through a contract with the FAA. It is standard production equipment.

The MLS equipment at Heathrow was located on runway 27R with the MLS azimuth antenna sited in front of the localizer antenna. The DME/P transponder was sited in close proximity to the azimuth antenna. The MLS ground equipment at Cardiff was placed in a more stressful configuration. The azimuth antenna was offset approximately 100 meters right of the runway 30 centerline, beyond the stop end of the runway. The elevation antenna was offset to the left of the runway 30 centerline in a "normal" location. The most stressful influence on MLS RNAV was provided by the DME transponder, which was sited on the control tower approximately 400 meters right of the runway centerline and about 1270 meters from the MLS azimuth antenna. Beside the siting irregularities, the DME transponder utilized a range offset to provide for zero range at the runway 30 threshold, not at the transponder. This prohibits the use of MLS RNAV guidance beyond the runway threshold.

GROUND TRACKING EQUIPMENT.

In order to determine MLS RNAV accuracy, a ground tracking system was employed at both Cardiff and Heathrow. The tracking system was developed by the FAA Technical Center. It provided for optical tracking in the lateral and vertical domains. The tracking system slews to a point light source on the aircraft of interest and provides for very accurate recording of aircraft angular position in space. Ranging information for reconstruction of the aircraft position is provided by very accurate C band distance measuring equipment. The tracking system, which is portable, was sited in the vicinity of the MLS elevation antennas at both Cardiff and Heathrow. The data recording rate of the tracking system is 10 hertz (Hz). Since the tracker is an optical system, tracking can be performed in both day and night visual conditions. Tracking was generally initiated with aircraft range between 14 and 18 miles from the tracker site.

CARDIFF, WALES, EVALUATION TESTS

MLS GROUND EQUIPMENT.

The siting of MLS equipment on runway 30 at Cardiff is depicted in figure 4. The azimuth antenna offset was 302 feet from the runway centerline. The Fernau Model 1117 DME transponder was sited in a difficult position 1002 feet from the runway centerline and over 4000 feet from the MLS azimuth antenna. A

complicating factor associated with the DME transponder was that the reply response time was set to yield a zero offset distance from the runway 30 threshold. This resulted in a sphere around the transponder in which MLS RNAV could not be conducted. It should also be noted that the azimuth antenna phase center was 13 feet below the runway datum.

The MLS geometry at Cardiff (azimuth to elevation antenna distance = 2200 meters and azimuth antenna offset distance = 92 meters) placed the azimuth antenna near the AWOP 13 recommended extremes of permissible azimuth offsets for computed centerline operations to the primary runway when using standard DME ranging information. The azimuth antenna siting limitations when using standard DME are presented in figure 5.

CARDIFF PROCEDURES.

Three different advanced MLS procedures were flown at Cardiff. The first procedure, shown in figure 6, was an MLS guided departure. Once the aircraft had climbed to 400 feet above ground level on runway heading, guidance switched to MLS RNAV guidance. Two miles from the end of the departure runway, a 110° left turn occurred. The turn was a closed loop turn with precision lateral guidance throughout the turn being provided by MLS RNAV. The aircraft leveled at 2500 feet mean sea level (m.s.l.) and continued on the new MLS RNAV track until it departed MLS coverage. This procedure demonstrated one aspect of MLS RNAV departures which have been shown to be of significant air traffic control (ATC) benefit in tests conducted at National Aeronautics and Space Administration (NASA) Ames Research Center and the National Aerospace Laboratory in Amsterdam. The positional accuracy of MLS reduces departure path lateral variability and provides a much more predictable ground track when compared to other forms of departure guidance.

A very complex approach procedure, shown in figure 7, was also flown at Cardiff. This procedure consisted of two precision 90° turns to a 2-mile final approach segment. Radar vectors were provided to intercept the procedure between waypoint 6, the glidepath intercept waypoint, and the initial waypoint for the procedure, waypoint 7. The first 90° turn occurred between waypoints 5 and 4. The turn to final, between waypoints 3 and 2, had the same 7500-foot turn radius. The glidepath was constant at 3°. This procedure was designed to demonstrate the flexibility of MLS RNAV and to permitted the validation of AWOP 13 recommendations concerning MLS computed centerline approach accuracies when using standard DME ranging equipment. The procedure also permits the evaluation of the use of standard DME for other than computed centerline operations to the primary runway.

The final procedure flown at Cardiff was a simple straight-in computed centerline approach to the primary runway. This procedure (depicted in figure 8) permitted data collection of lateral accuracy data to verify recommendations made by AWOP 13.

Subject pilots flew the "S" pattern approach and MLS RNAV departure on 3 different days at Cardiff. Thirteen different pilots flew the procedures. The straight-in computed centerline approach was only flown by FAA test pilots. Each pilot who participated in the evaluation was asked a series of questions immediately following his flight experience. The questionnaire results can be found in appendix B.

CARDIFF MLS RNAV RESULTS.

Using ground tracking data and airborne recordings, analysis of MLS RNAV accuracies was made. The statistical values presented in table 2 represent the results for an approach run from where the tracking started in nautical miles from the threshold to threshold crossing. The lateral accuracy for the straight-in procedures exceeds lateral accuracy performance guidelines presented in the AWOP 13 recommendations. The guidance material identifies a 95 percent lateral error value of 50 feet at the decision height location. This is less than the lateral accuracy requirements for Category I ILS procedures. It is noted that the lateral accuracy for the straight-in procedures met the requirement for the entire length of the approach in all cases. The largest observed 95 percent value was slightly larger than 30 feet.

TABLE 2. MLS RNAV ACCURACY WHEN USING STANDARD DME

Procedure	Sample Size	Computed Lateral Error (ft) Mean	95%	Computed Vertical Error (ft) Mean	95%	Track Start
Computed	1435	-6.2	21.1	-31.1	43.8	16 nmi
Centerline	1790	-11.3	25.1	-27.4	48.4	17 nmi
	1974	-14.1	21.6	-9.0	64.6	16 nmi
	1374	-22.3	30.8	-9.2	34.8	20 nmi
	1436	-6.7	21.6	-20.1	46.5	18 nmi
	1794	-6.0	25.8	-16.6	58.4	18 nmi
"S" Pattern	1912	157.2	216.8	79.5	124.1	11 nmi
	1726	-203.8	210.6	43.8	110.8	11 nmi
	1179	-192.0	180.4	69.7	106.4	14 nmi

Since the computed centerline operation is conducted to the primary runway, basic MLS elevation guidance is sufficient and use of computed vertical position is not required. However, to verify that standard DME does not provide the necessary accuracy for vertical position computation, computed vertical position data were also collected. The recommended vertical accuracy at decision height is 15 feet. The vertical error statistics indicate Standard DME ranging does not result in computed vertical position accuracy meeting the recommended vertical accuracy at decision height.

The large increase in the lateral errors for the "S Pattern" results because of the much greater lateral offset of the procedure from the azimuth antenna. Additionally, between waypoints 5 and 2, error contribution from range information increases significantly. Between these waypoints the error associated with the standard DME couples more strongly into the lateral position estimate. In fact, when flying perpendicular to the final approach course lateral position error is almost equal to the DME ranging error. Results obtained at Cardiff indicate standard DME range accuracies will only support computed centerline operations to the primary runway, subject to the limitations in the ICAO recommendations.

Figure 9 depicts the cross-track error, in feet, as a function of distance from runway threshold for one straight-in approach. From the threshold to a

range of 5 miles, the cross-track error was significantly less than the recommended 50-foot lateral accuracy at decision height. Even beyond 7 miles, the 50-foot lateral accuracy recommendation was rarely exceeded. All straight-in lateral error plots for each of the approaches was similar to the lateral accuracy performance depicted in figure 9.

The inaccuracy that results when standard DME is used for vertical position computation is presented in figure 10. A vertical position bias error on the order of 55 feet begins about 6 miles from threshold. It remains fairly constant until in the immediate vicinity of the runway threshold. It should be noted that during the tests at Cardiff, a fairly consistent bias of about 420 feet was detected in the measured slant range. This resulted with DME/P interrogation with the SEL interrogator of a standard DME transponder. The error magnitude does meet standard DME accuracy requirements.

The ability of the pilot to laterally track the computed centerline procedure is presented in figure 11. Throughout the procedure, lateral deviations were less than 0.35°. This value represents less than 12 percent full scale cross-track deviation. This indicates that the use of standard DME ranging information for computed centerline operations to the primary runway resulted in not only accurate but smooth, easy to fly lateral guidance. For the primary runway computed centerline operation, basic elevation angle data provides the vertical guidance function. As a result, the smoothness of the vertical guidance is not an issue.

"S" PATTERN FLYABILITY.

Although standard DME ranging did not permit the necessary accuracy to be obtained on the MLS RNAV "S" approach, measures of the pilot's ability to laterally and vertically track the advanced procedure were obtained. The pilot's ability to laterally track the "S" pattern procedure is presented in figure 12. Recall the first 90° right turn occurred between waypoints 5 and 4 and the second 90° left turn occurred between waypoints 3 and 2. From waypoint 6 to the threshold, the largest lateral deviation is less than 0.60° (less than 20 percent full scale). This deviation occurred at the entry to the second 90° turn. The large deviation beyond 8.26 nmi represents the deviation while the pilot was intercepting the procedure between waypoints 7 and 6 and was not tracking the procedure. The results indicated that the pilot could accurately track the "S" pattern in the lateral domain.

Similarly, figure 13 depicts the pilot's vertical tracking performance. The trace begins at waypoint 6 because that is where the 3° glidepath was intercepted. Maximum deviations on the order of 0.25° (25 percent full scale) occurred during the first 90° turn and in the vicinity of decision height. Excellent vertical path tracking resulted.

Another issue investigated was the aircraft pitch and roll history during this advanced MLS approach. The nominal ground speed for the approaches was 140 knots. In figure 14, the aircraft roll history is presented. The peak roll angles observed were about 22° and occurred at entry to the second 90° turn. Peak roll values for the first turn were about 17°.

The MLS advanced procedure aircraft pitch history is presented in figure 15. Prior to glidepath intercept (waypoint 3), a consistent +5 pitch is exhibited. After glidepath intercept, nothing remarkable is detected.

HEATHROW AIRPORT EVALUATION TESTS

MLS GROUND EQUIPMENT.

MLS equipment has been sited on runway 27 right for several years to support United Kingdom MLS data collection with an in-service Boeing 757. However, to conduct the advanced MLS operations to runway 27L, it was necessary to locate a DME/P transponder at Heathrow Airport. The transponder was provided by the FAA. The transponder is production equipment meeting the standard 1 DME/P requirements in reference 3. Figure 16 depicts the MLS ground equipment configuration at Heathrow Airport. The azimuth antenna was located on the runway 27R extended centerline in front of the localizer antenna. The MLS elevation antenna was sited in the vicinity of the ILS glide slope antenna. The DME/P transponder was sited near the azimuth antenna. This siting configuration represents the normal siting on runway 27R. This siting also conforms to the recommended procedure for collocating MLS with ILS.

Figure 16 also depicts the relative location of runway 27L to the MLS equipment. Runway 27L is parallel to the primary MLS runway 27R. The lateral separation between the runways is more than 4600 feet. The runway separation is located at the extremes of permissible parallel runway separations for computed centerline operations identified in AWOP 13 recommendations. When making a computed centerline approach to runway 27L, the runway threshold is located 20° off the azimuth antenna boresight. The lateral angle from the MLS elevation antenna to the runway threshold exceeds 85°. The relationship between the MLS equipment siting environment at Heathrow and the AWOP 13 recommendations is presented in figure 17. It should be noted the runway stagger at Heathrow is also a complicating factor. The threshold of runway 27L is staggered away from the threshold of runway 27R. The ideal situation would have the secondary runway staggered forward from the primary runway in order to improve elevation coverage for the computed centerline operation to the secondary runway.

HEATHROW AIRPORT PROCEDURES.

Two different advanced MLS approach procedures were flown at Heathrow Airport. The first procedure is depicted in figure 18. Because of the large separation from the MLS primary runway, both lateral and vertical guidance were computed. The 3° glidepath was intercepted at waypoint 2, the final approach fix. This resulted in a final approach segment length of 8 nmi. Threshold crossing height for the procedure was 50 feet. Waypoint 1 on the approach plate is the threshold crossing point for runway 27L. In order to meet Category I vertical accuracy requirements, conic correction for elevation signal propagation is required and included in the vertical computation. Waypoint 0 is the limit of azimuth coverage on runway 27L.

The second procedure flown at Heathrow Airport was designed to demonstrate the flexibility of MLS RNAV in the vertical domain. This procedure, depicted in figure 19, was flown to runway 27R. It incorporated a transition from a 4.5° glidepath to a final 3.0° degree glidepath. Although not all air carrier aircraft are capable of this vertical profile, the procedure would be of benefit where an obstacle beyond 3.5 or 4 miles from the threshold prevents the use of a standard 3° glidepath. Another benefit would be possible noise reduction. It is noted the 4.5° glidepath is measured relative to waypoint 2

and not the runway datum. The transition in the glidepath is a closed loop transition with vertical guidance being display relative to the aircraft's current along track position.

WIDELY SEPARATED PARALLEL RUNWAY RESULTS.

A total of five approaches were flown to runway 27L. Pilots who flew the approaches were civilian or military pilots from the United Kingdom and the United States. Excellent vertical guidance was available to threshold crossing. At this location the lateral angle to the elevation antenna was more than 85°. The azimuth angle was 20° at the threshold. Figure 20 depicts the received elevation angle as a function of range for one of these five approaches. The computed glidepath was 3°. As the aircraft progresses closer to the threshold on this computed glidepath, the conic propagation pattern of the elevation signal becomes more pronounced. At threshold crossing, waypoint 1, the received elevation angle is less than 1.2°. Figure 20 vividly identifies the need for conic correction in vertical guidance. The excellent result that is obtained when conic correction is used is presented in the observed vertical errors at DH depicted in table 3.

VERTICAL GUIDANCE TO A WIDELY SEPARATED PARALLEL RUNWAY.

The fact that vertical guidance is present to the threshold indicates excellent elevation signal coverage well beyond the coverage volume described in reference 3. The runway threshold is more than 2800 feet (850 meters) inside the normal Category I decision height position.

The flyability of the vertical guidance to runway threshold is shown in figure 21. Full scale vertical display sensitivity was set to +/- 1°. Even at the threshold, less than 1/2 scale vertical displacement is present. The vertical displacement is generally limited to 1/4 full scale or less from glidepath intercept to the threshold. The error presented in figure 21 represents vertical flight technical error (FTE).

LATERAL GUIDANCE TO A WIDELY SEPARATED PARALLEL RUNWAY.

Accurate lateral guidance was provided to the limits of azimuth coverage more than 6000 feet down the runway from the landing threshold. This demonstrated the excellent performance of MLS at Heathrow. Figure 22 depicts the lateral performance that was observed on one approach. As shown, azimuth angle data were available more than two-thirds the way down the runway. The quality of the lateral guidance is presented in figure 23. Here, the cross-track deviation (cross-track error (CTE)) is depicted as a function of range for one approach. Full scale sensitivity was set to +/- 3°. Very consistent lateral tracking by the pilot existed to threshold crossing. Maximum cross-track deviations (lateral FTE) were consistently less than 1/6 full scale to the runway threshold. Beyond the threshold, the cross-track deviations increase as the pilot initiated a go-around procedure.

Of the five approaches made to runway 27L, ground tracking data were available for four of the approaches. Table 3 presents the tracking results. The statistics represent the error data collected over the entire approach from the start of tracking to threshold crossing. Of particular interest is the error at decision height. The entries in the column labeled error at decision height represent the error observation that resulted from data taken closest

to the decision height location. Excellent performance over the entire approach was observed. The data taken in the vicinity of decision height met criterion established in references 1 and 2.

TABLE 3. POSITION ESTIMATION ERRORS FOR WIDELY SEPARATED PARALLEL RUNWAY APPROACHES

Approach	Sample	95% Error (ft)		Error at DH (ft)	
Number	Size	Lateral	Vertical	Lateral	Vertical
1	540	63.9	20.6	-46.2	5.4
2	788	68.4	25.2	-47.5	6.7
3	1336	82.4	28.2	-40.5	13.1
4	1004	62.4	(no data)	-41.1	(no data)

Figure 24 depicts the observed vertical error for one approach to runway 27L. The excellent, consistent performance presented in figure 24 was repeated on every runway 27L approach.

RUNWAY 27R (TWO-SEGMENT GLIDEPATH) PROCEDURE.

The glidepath transition in this occurs at waypoint 2. The glidepath transition at waypoint 2 does not cause any pilot tracking difficulties. At waypoint 2 the average pitch attitude changes from 2° for the 4.5° glidepath (waypoint 3 to waypoint 2 segment) to 5.5° average pitch attitude for the 3.0° glidepath between waypoints 2 and 1.

Vertical tracking performance for this approach is presented in figure 25. The vertical flyability is presented in figure 26. In figure 26 the vertical deviation during the transition at waypoint 2 does not exceed 1/5 full scale. Throughout the entire procedure from glidepath intercept to threshold, vertical deviations do not exceed 1/4 full scale.

Similarly, the lateral FTE deviations shown in figure 27 indicate no lateral tracking problem at waypoint 2 where the vertical profile transition occurs. Throughout the procedure, cross-track deviations did not exceed 1/5 full scale.

Five different pilots flew the MLS RNAV procedures at Heathrow Airport. Their acceptance of the MLS RNAV procedures flown was very positive. Their specific responses to questions concerning the procedures flown at Heathrow are presented in appendix C.

OTHER RESULTS

This demonstration provided the vehicle for evaluation of specific recommendations made at AWOP 13. It also provided for the demonstration of equipment designed to meet the requirements identified in ICAO documentation. Several different States participated in this evaluation with equipment manufactured by several different States being used in this evaluation. Table 4 presents the various MLS components used in this evaluation along with their State of origin.

There was no difficulty during the evaluation with the operation of any equipment combination employed. This indicates the system design based on ICAO documentation resulted in excellent equipment interoperability.

TABLE 4. MLS EQUIPMENT USED IN THE FLIGHT EVALUATIONS

Component	Model	Manufacturer	State of Origin
Receiver	20A	Bendix/King	USA
Receiver	M2000	Canadian Marconi	Canada
Receiver	JLB-102	Japan Radio Corp.	Japan
Azimuth, Elevation Systems		Siemens-Plessy, Ltd.	United Kingdom
DME/P Interrogator	SEL 400	Standard Electric Lorenz	Germany
DME/P Transponder		E-Systems	USA
Standard DME Transponder	1117	Fernau, Ltd.	United Kingdom

CONCLUSIONS AND RECOMMENDATIONS

Based on the flight evaluations conducted at Cardiff, Wales, Airport and at Heathrow Airport in London, England, several conclusions can be made.

1. Distance measuring equipment (DME) meeting standard DME requirements provides sufficient ranging accuracy to meet computed lateral accuracy requirements for computed centerline operations to the primary Microwave Landing System (MLS) runway. However, the azimuth antenna offset distance from the runway centerline should not exceed the limits identified in All Weather Operations Panel (AWOP) 13 recommendations. These limitations in offset distances can be removed with the use of precision distance measuring equipment (DME/P).

2. DME meeting standard DME requirements does not provide sufficient accuracy to support computed vertical position estimates in MLS RNAV applications.

3. DME meeting standard DME requirements does not provide sufficient accuracy to support computed lateral position estimates when the aircraft is flying advanced MLS RNAV procedures and the procedure lateral track is not aligned with the primary runway.

4. The azimuth antenna offset limitations for standard DME equipment contained in the AWOP 13 recommendations are correct. The evaluation at Cardiff utilized a ground equipment geometry that placed the azimuth antenna at the extremes of permissible azimuth antenna offsets identified in AWOP 13 recommendations.

5. The range of application of computed centerline operations to the secondary runway identified in AWOP 13 recommendations is correct. The relationship of the secondary parallel runway at Heathrow to the MLS equipment was located at the very extremes of both the runway separation and runway stagger values.

6. For computed centerline operations to secondary parallel runways, DME/P must be used. The use of DME/P is necessary because vertical position must also be computed to eliminate the conic effect in the propagated elevation signal. DME/P accuracies are required when computing vertical position.

7. Excellent equipment interoperability was demonstrated during the evaluation. Equipment manufactured in five different countries was used in various combinations with no difficulty.

8. The results of the flight tests have validated recommendations made in appendix B.

It is recommended that the results of this evaluation be presented to the various organizations developing standards for MLS avionics equipment.

REFERENCES

1. International Civil Aviation Organization, All Weather Operations Panel Thirteenth Meeting, Montreal, Canada, March 5-23,1990.

2. Minimum Operational Performance Standards for Airborne MLS Area Navigation Equipment, Document No. RTCA/DO 198, March 15, 1988.

3. International Standards Recommended Practices and Procedures for Air Navigation Services, Aeronautical Telecommunications Annex 10 to the Convention on International Civil Aviation, April 1985.

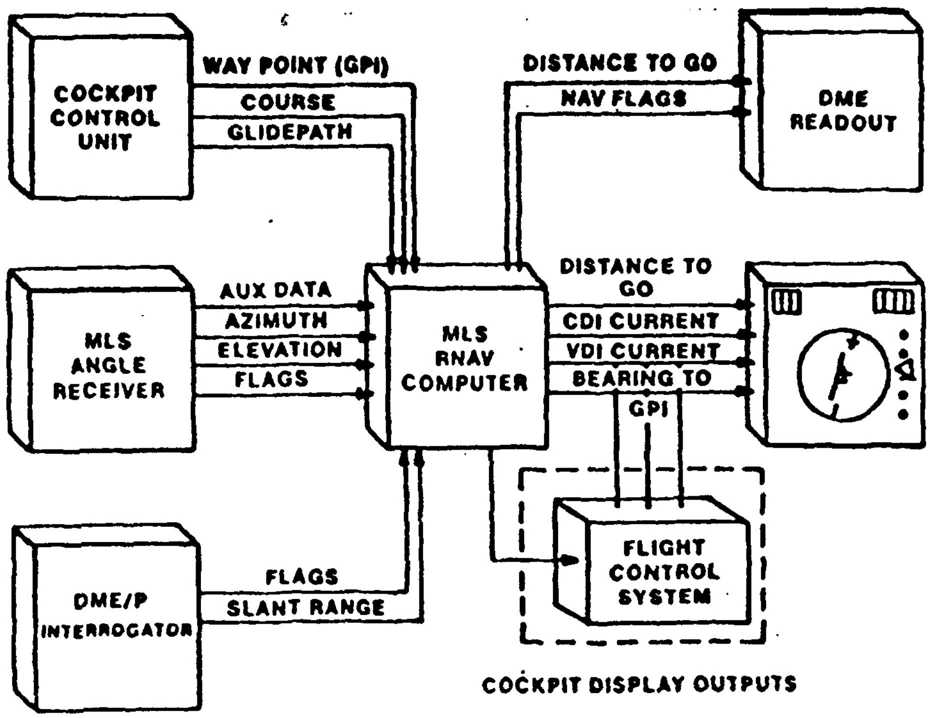

FIGURE 1. MLS RNAV AVIONICS SUITE

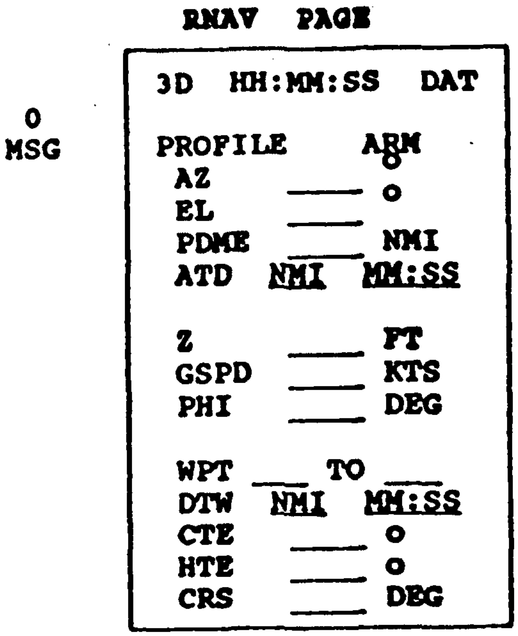

FIGURE 2. MLS COCKPIT CONTROL DISPLAY UNIT

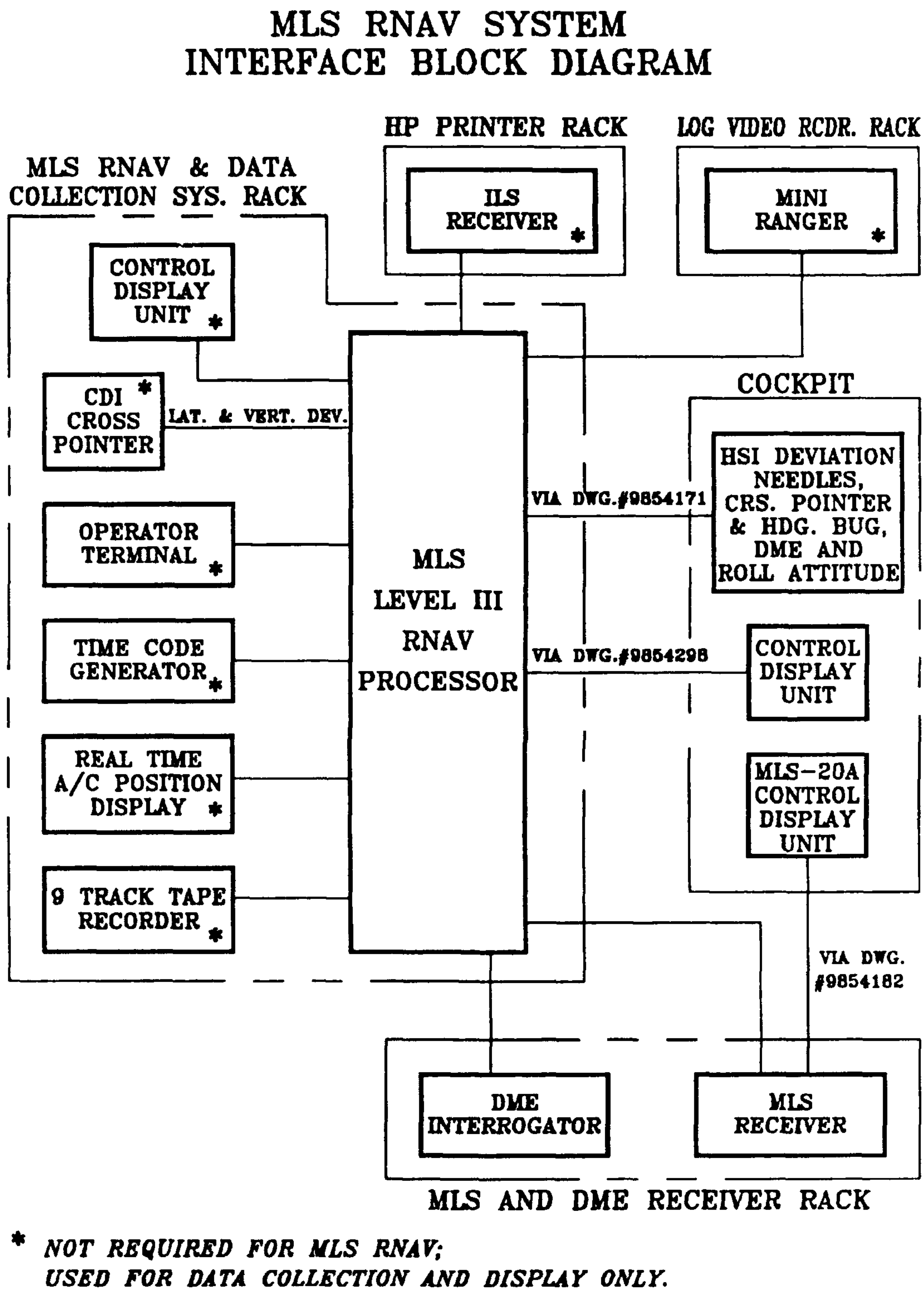

FIGURE 3. AIRBORNE FLIGHT DATA COLLECTION SYSTEM

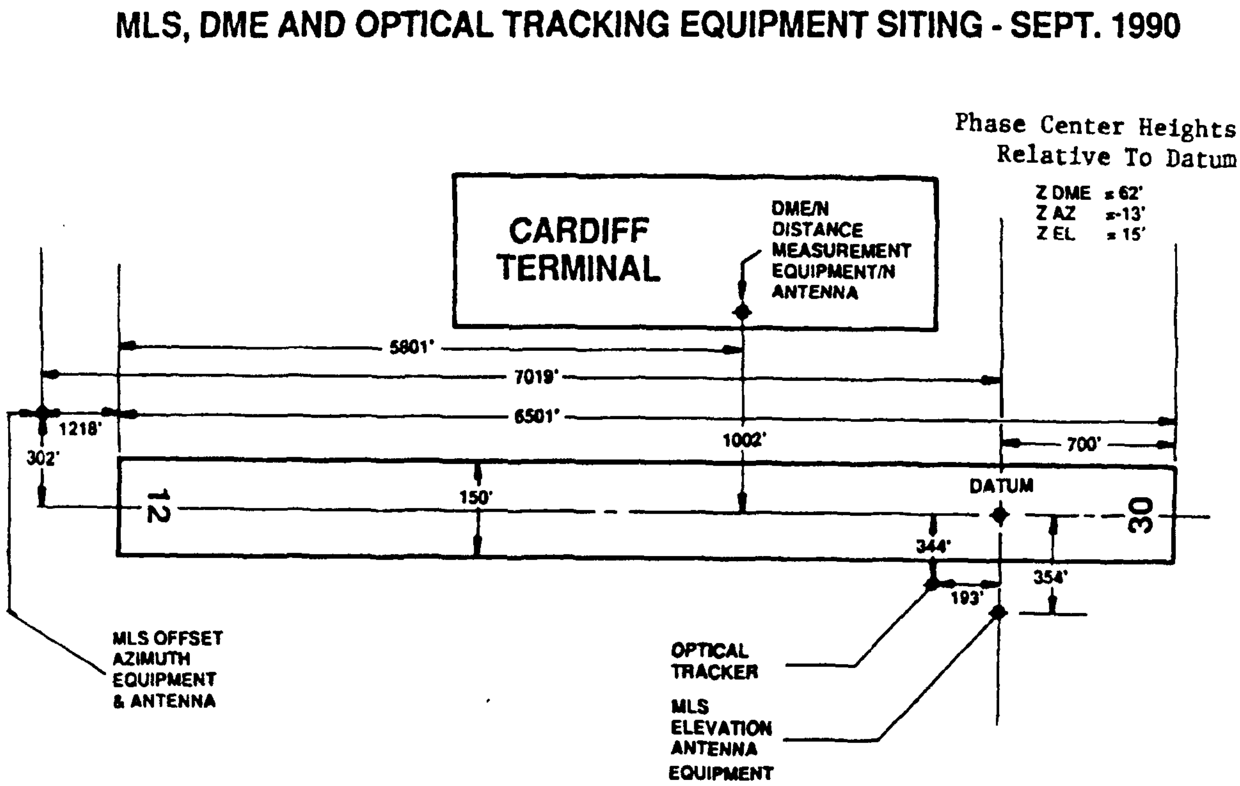

FIGURE 4. MLS SITING CONFIGURATION AT CARDIFF, WALES

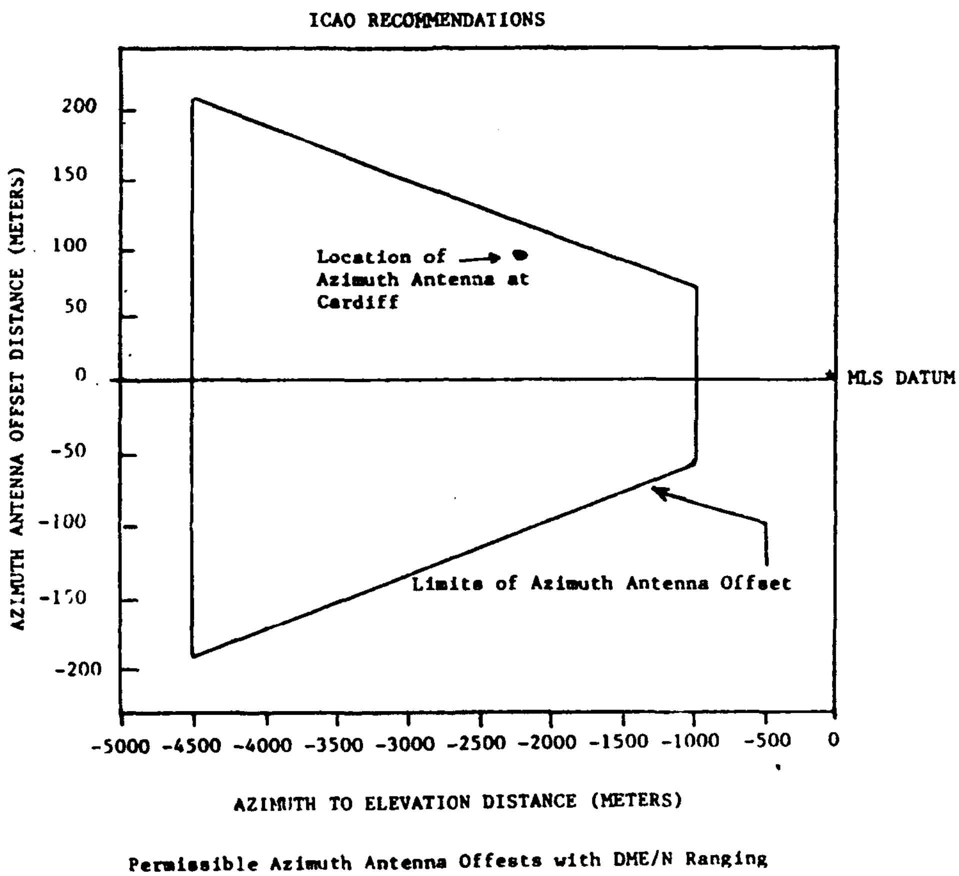

FIGURE 5. PERMISSIBLE AZIMUTH ANTENNA OFFSETS WITH STANDARD DME

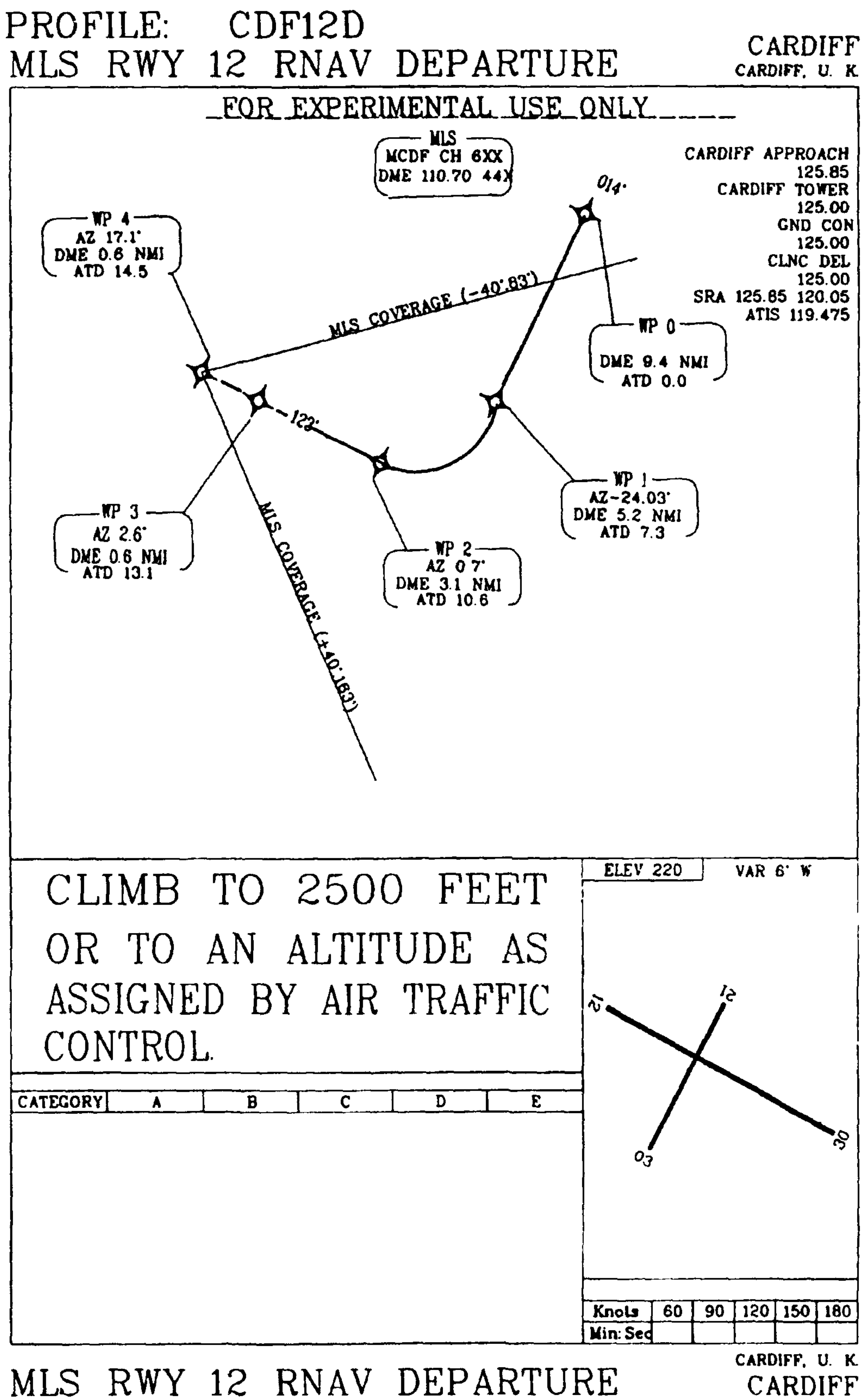

FIGURE 6. MLS RNAV DEPARTURE PROCEDURE

PROFILE: CDF30B
MLS RWY 30 RNAV

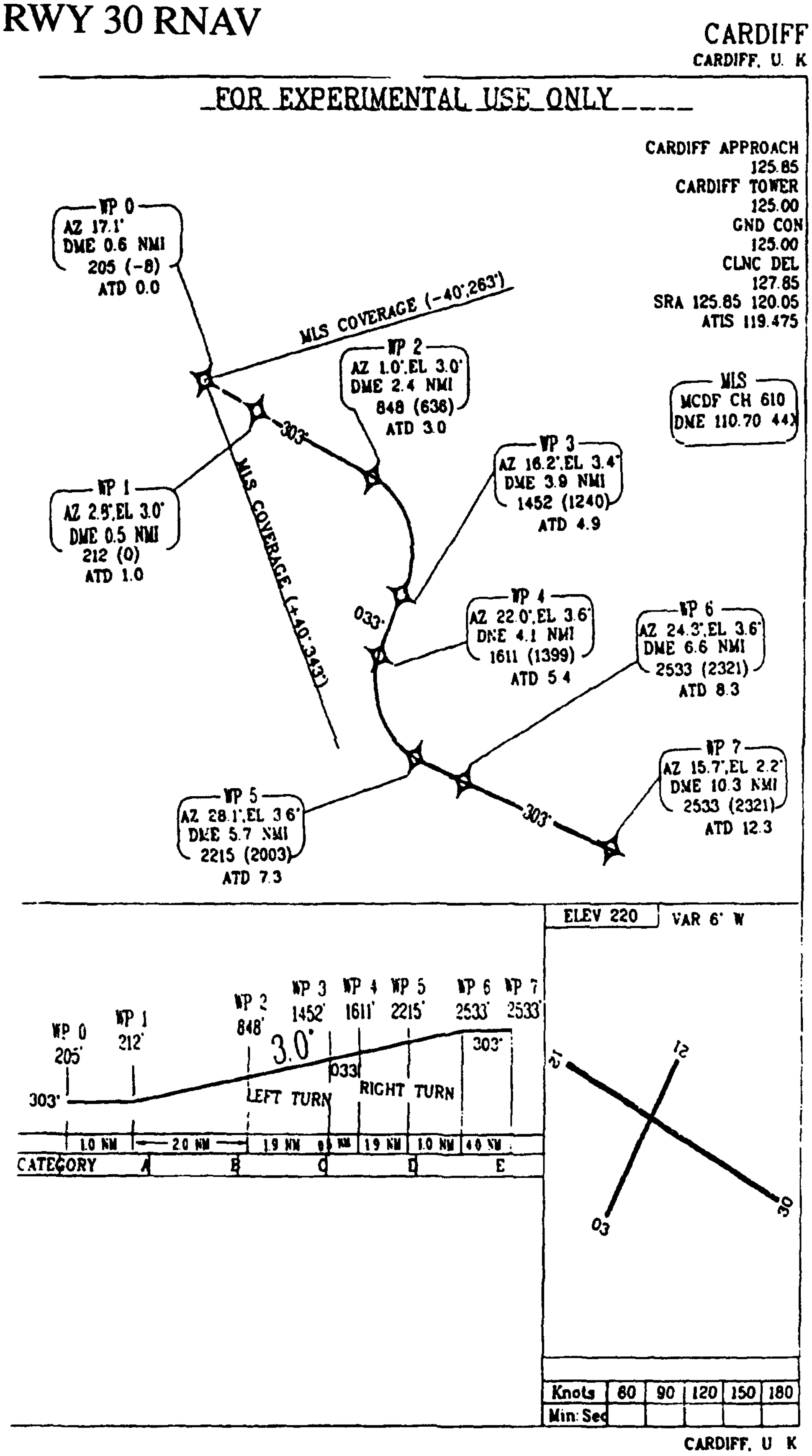

FIGURE 7. "S" PATTERN APPROACH PROCEDURE AT CARDIFF, WALES

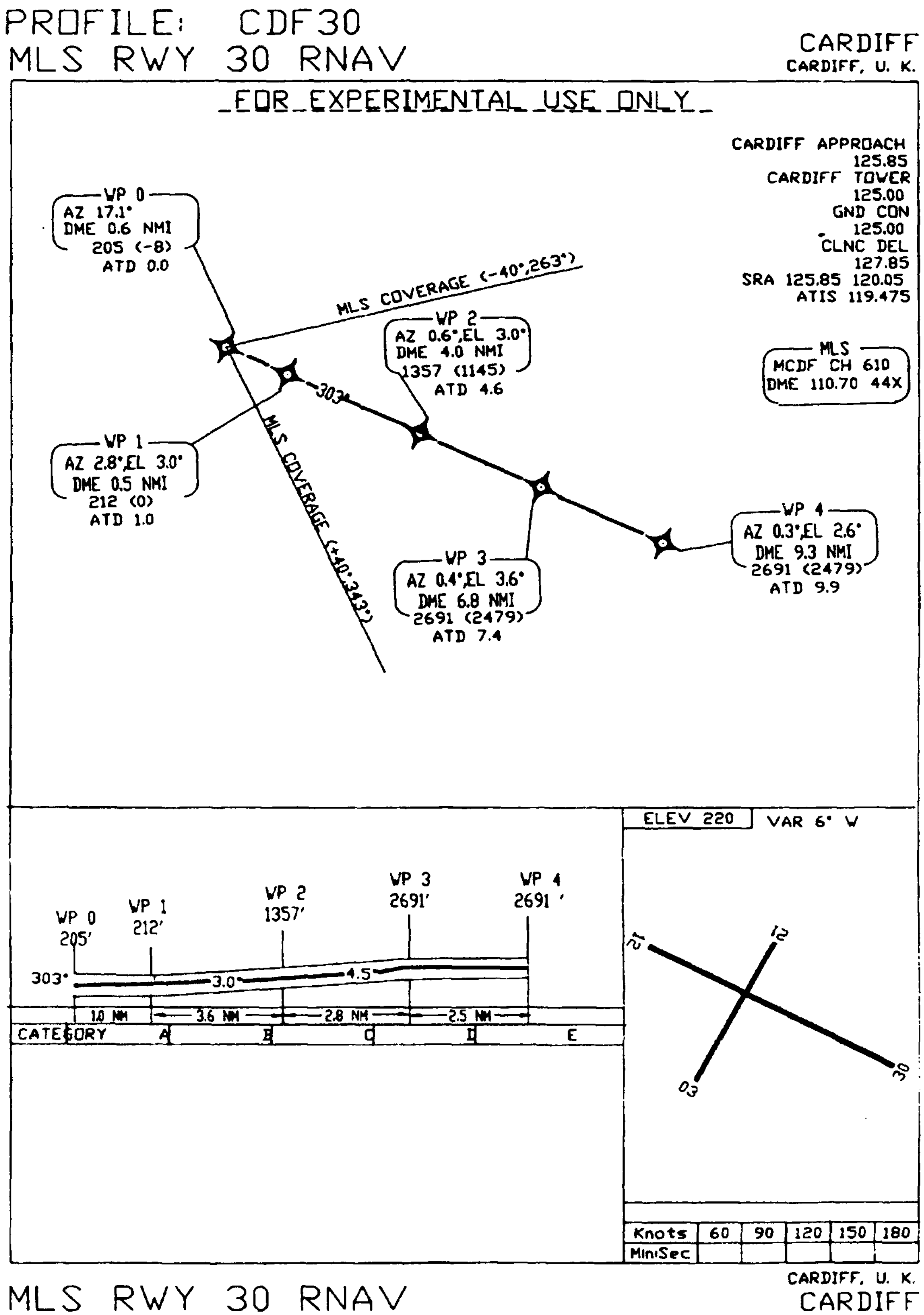

FIGURE 8. STRAIGHT-IN COMPUTED CENTERLINE PROCEDURE

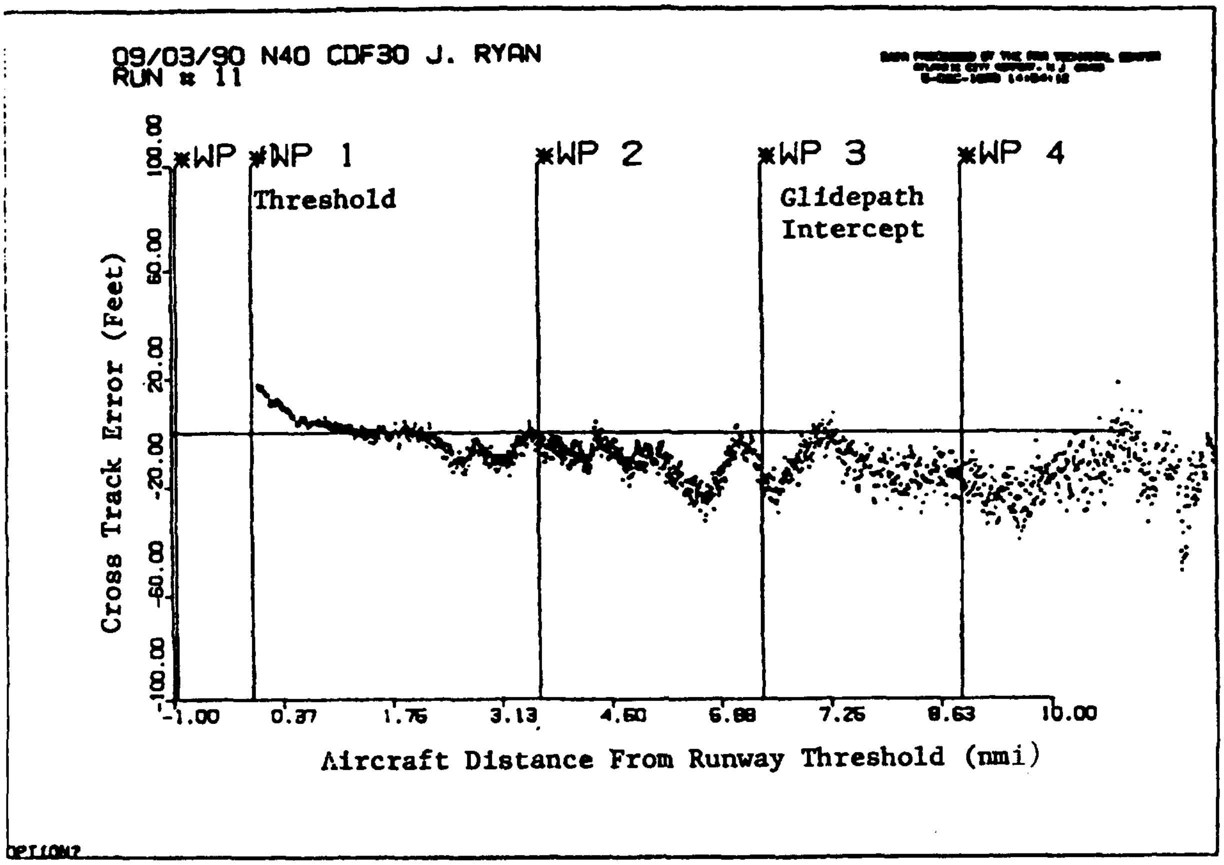

FIGURE 9. LATERAL ACCURACY FOR COMPUTED CENTERLINE APPROACH TO RUNWAY 30 AT CARDIFF

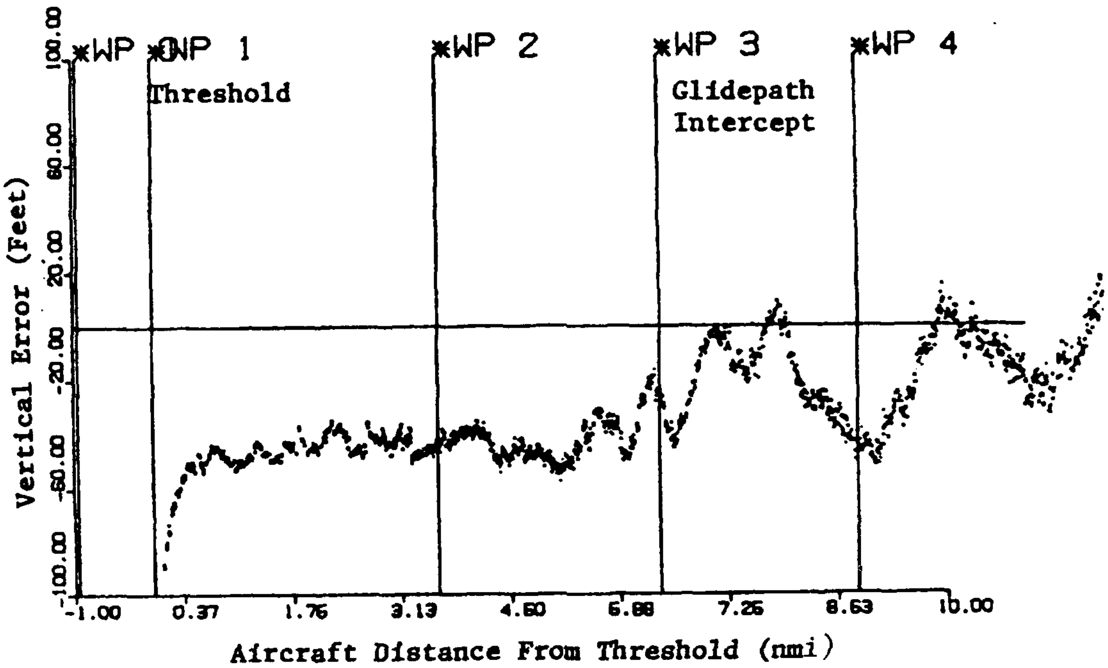

FIGURE 10. VERTICAL ACCURACY BASED ON STANDARD DME

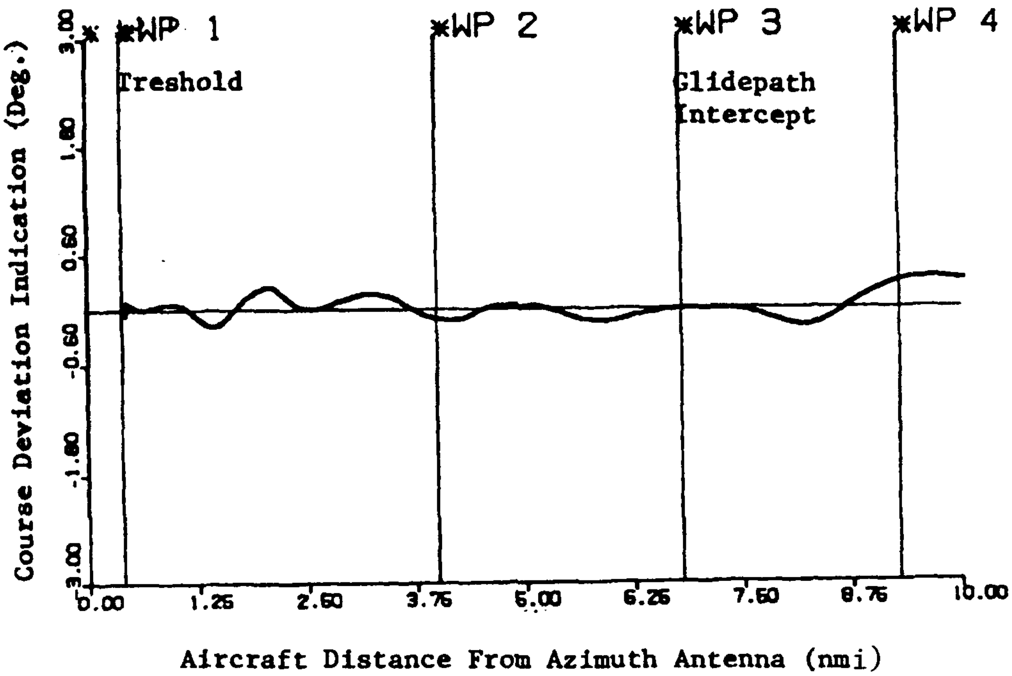

FIGURE 11. DISPLAYED CROSS-TRACK DEVIATIONS DEPICTED AS A FUNCTION OF RANGE FROM THE AZIMUTH ANTENNA

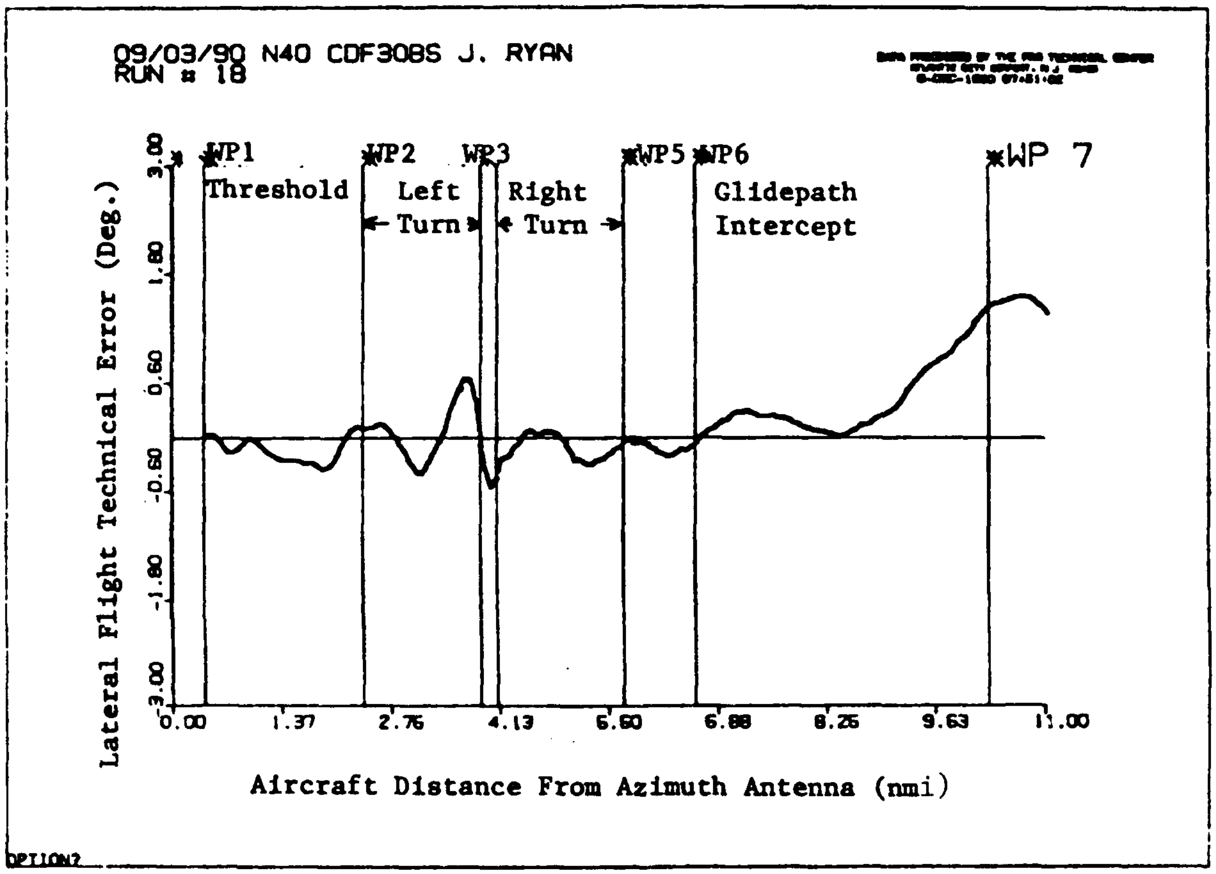

FIGURE 12. LATERAL FLIGHT TECHNICAL ERROR

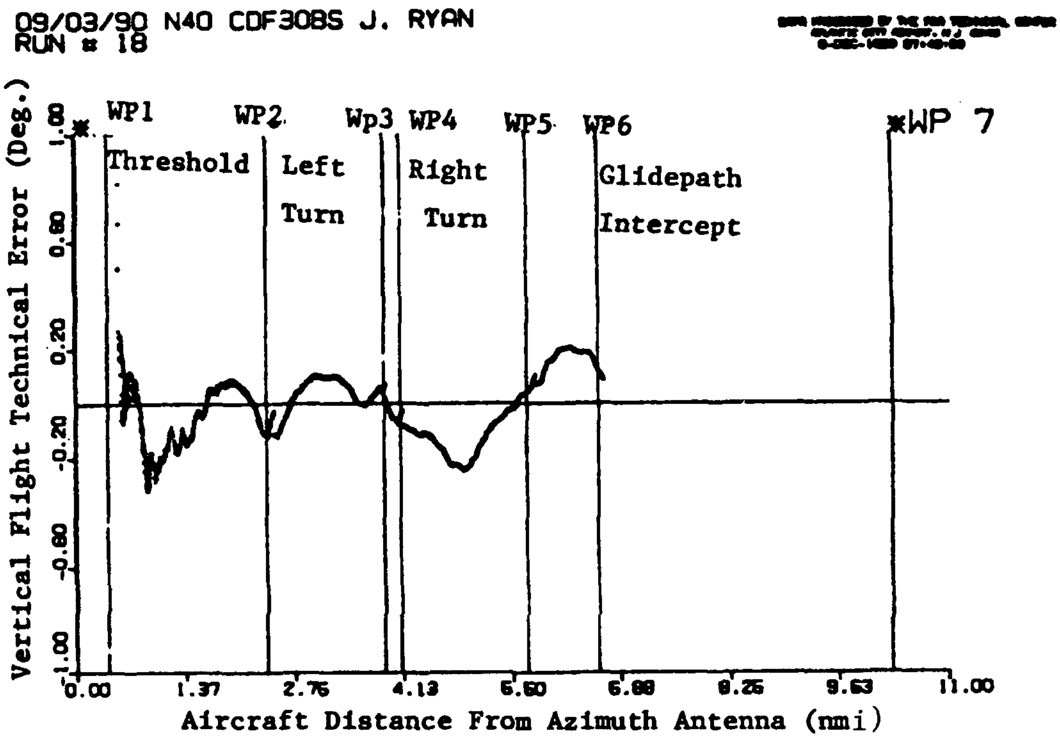

FIGURE 13. VERTICAL FLIGHT TECHNICAL ERROR

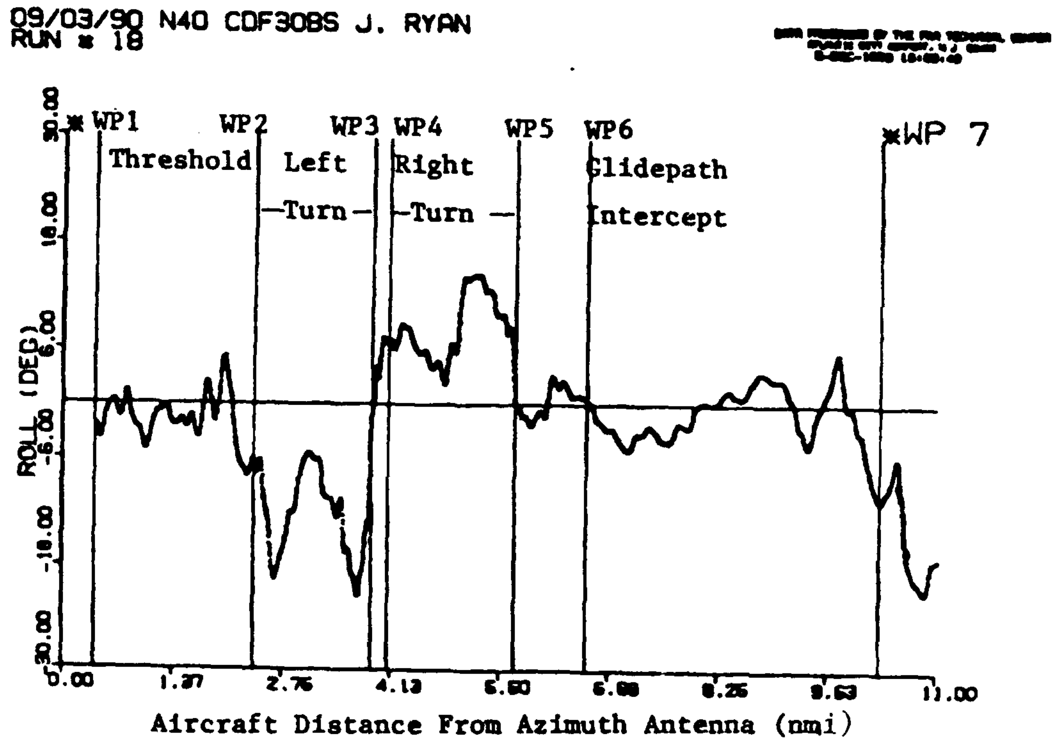

FIGURE 14. AIRCRAFT ROLL HISTORY ON THE "S" PATTERN APPROACH

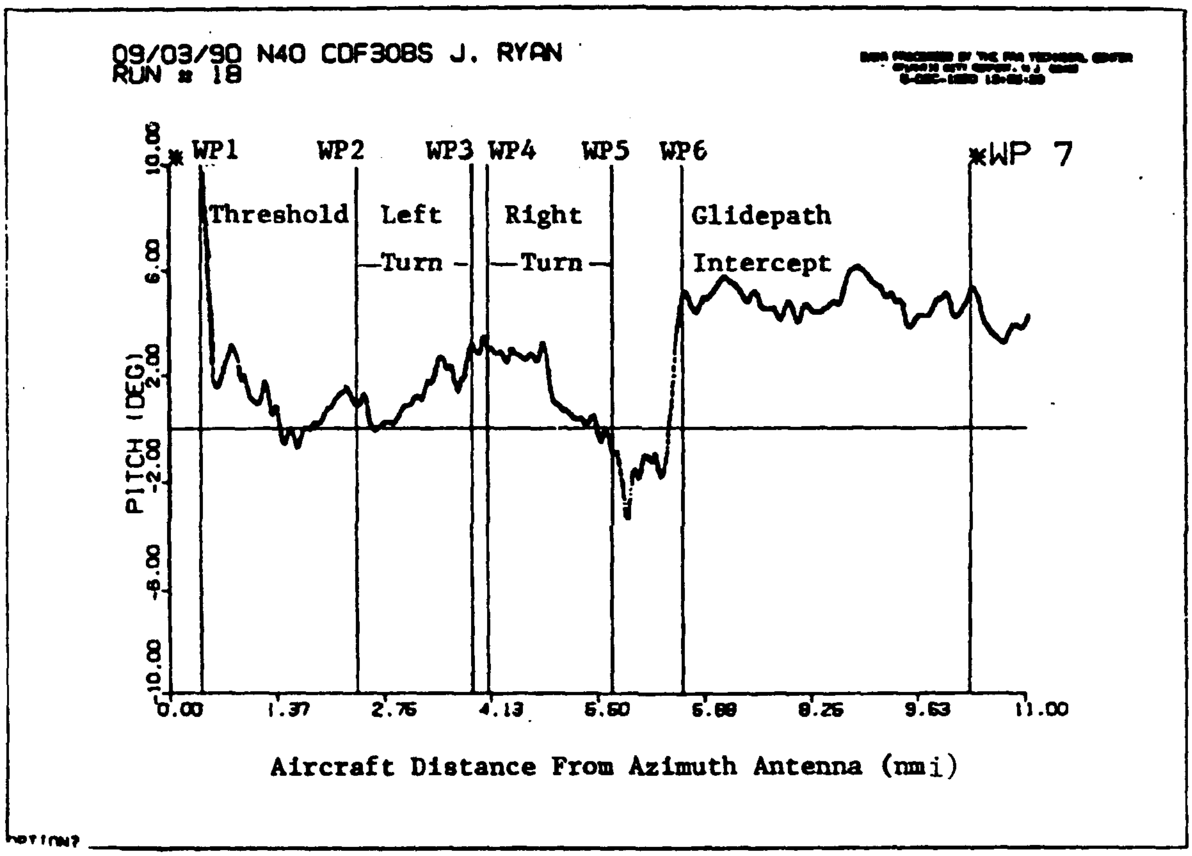

FIGURE 15. AIRCRAFT PITCH HISTORY DURING ADVANCED MLS APPROACH

MLS, DME AND OPTICAL TRACKING EQUIPMENT SITING - SEPT. 1990

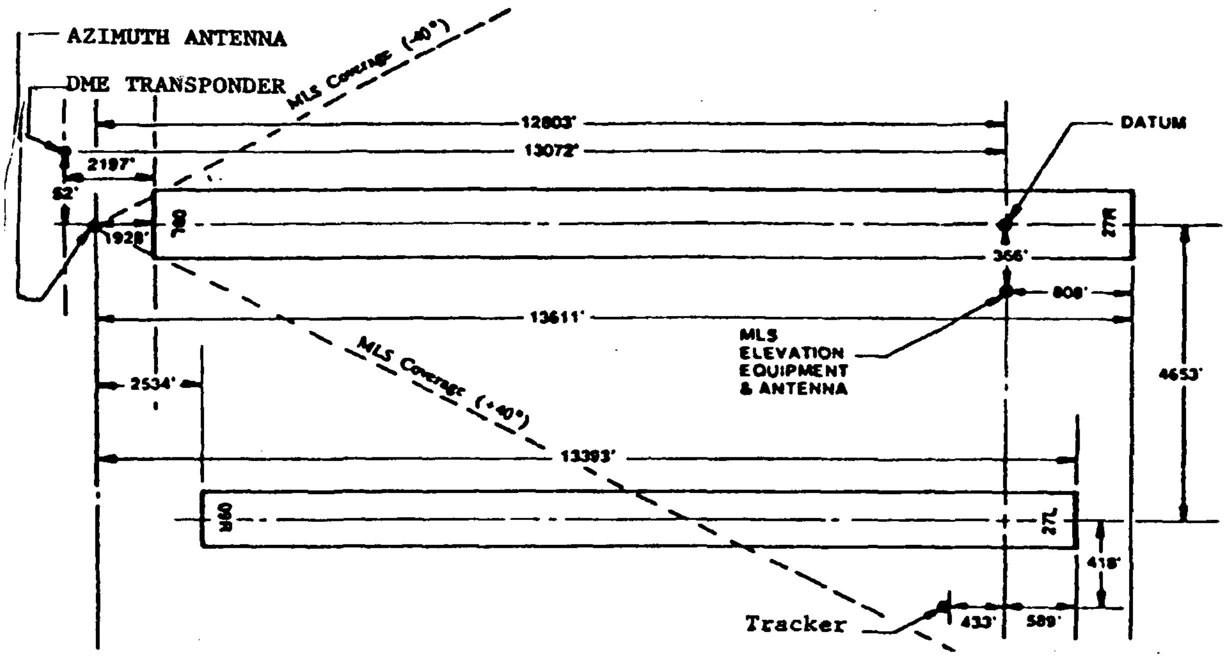

FIGURE 16. MLS EQUIPMENT SITING AT HEATHROW AIRPORT

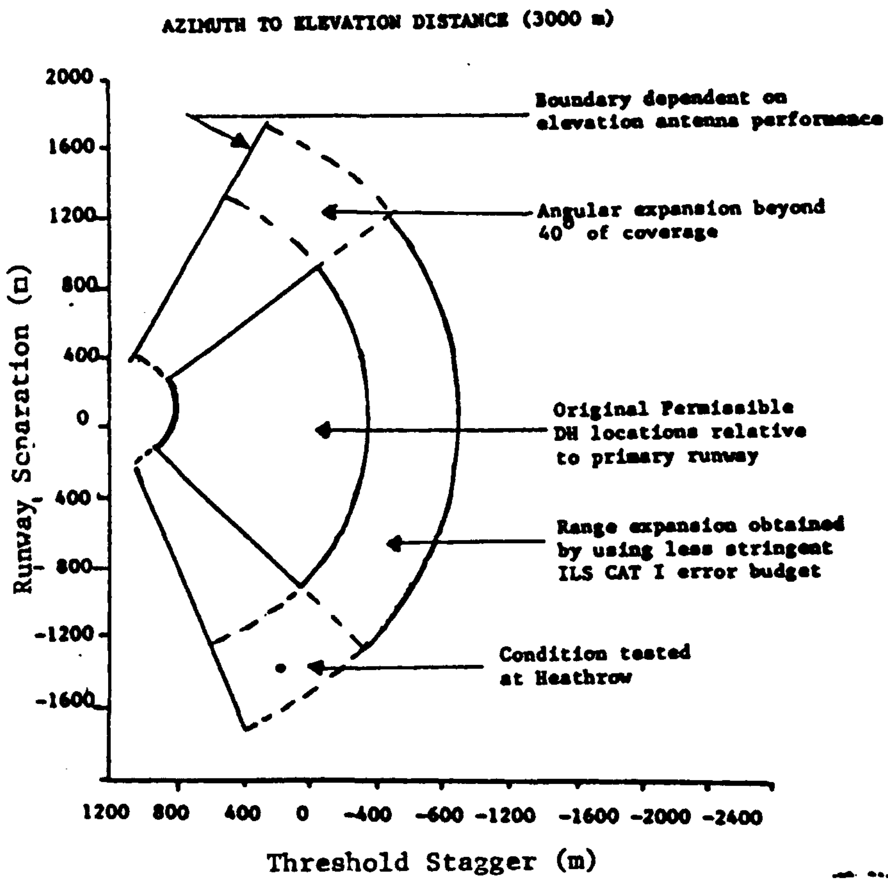

FIGURE 17. PERMISSIBLE PARALLEL SECONDARY RUNWAY LOCATIONS

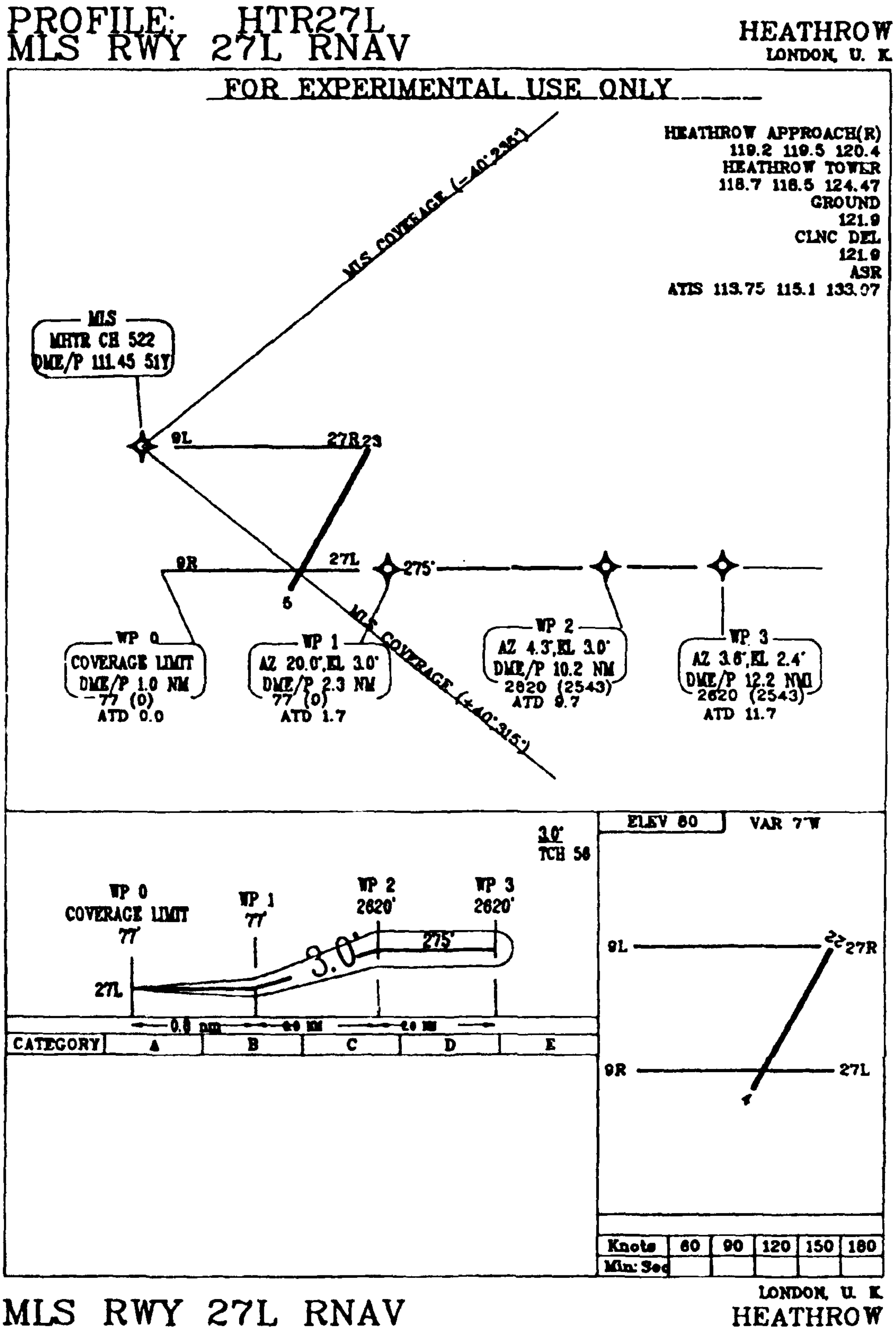

FIGURE 18. COMPUTED CENTERLINE APPROACH TO A WIDELY SEPARATED PARALLEL RUNWAY

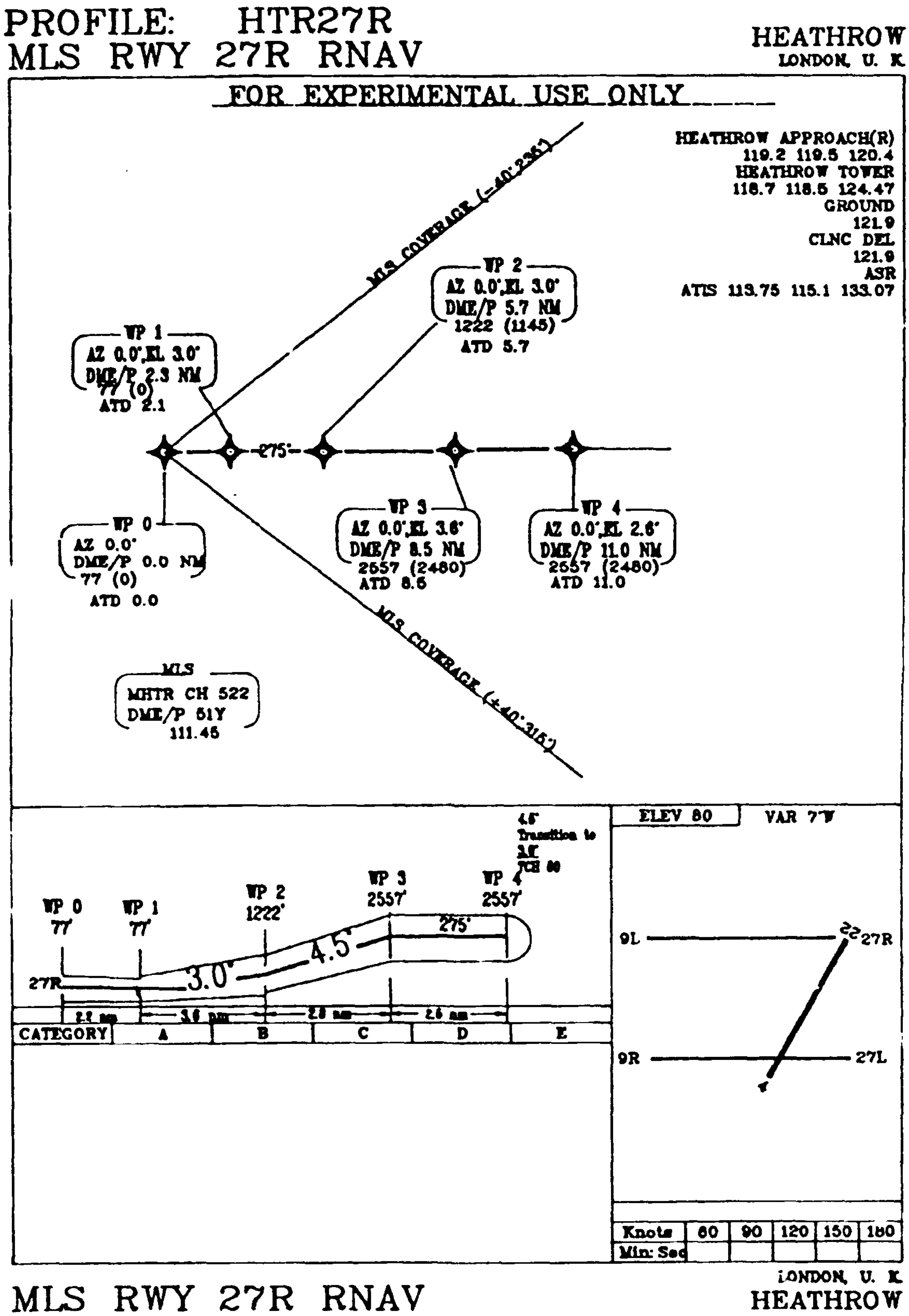

FIGURE 19. TWO SEGMENT GLIDEPATH PROCEDURE AT HEATHROW AIRPORT

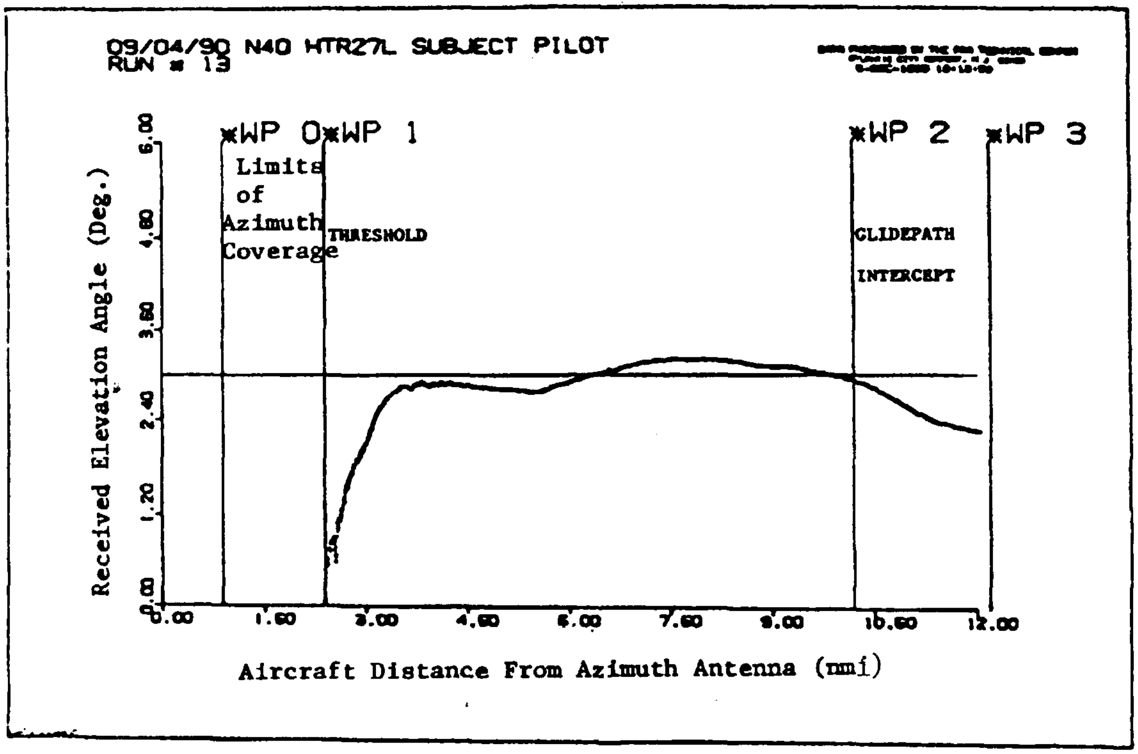

FIGURE 20. RECEIVED RAW ELEVATION ANGLE ON A RUNWAY 27L APPROACH

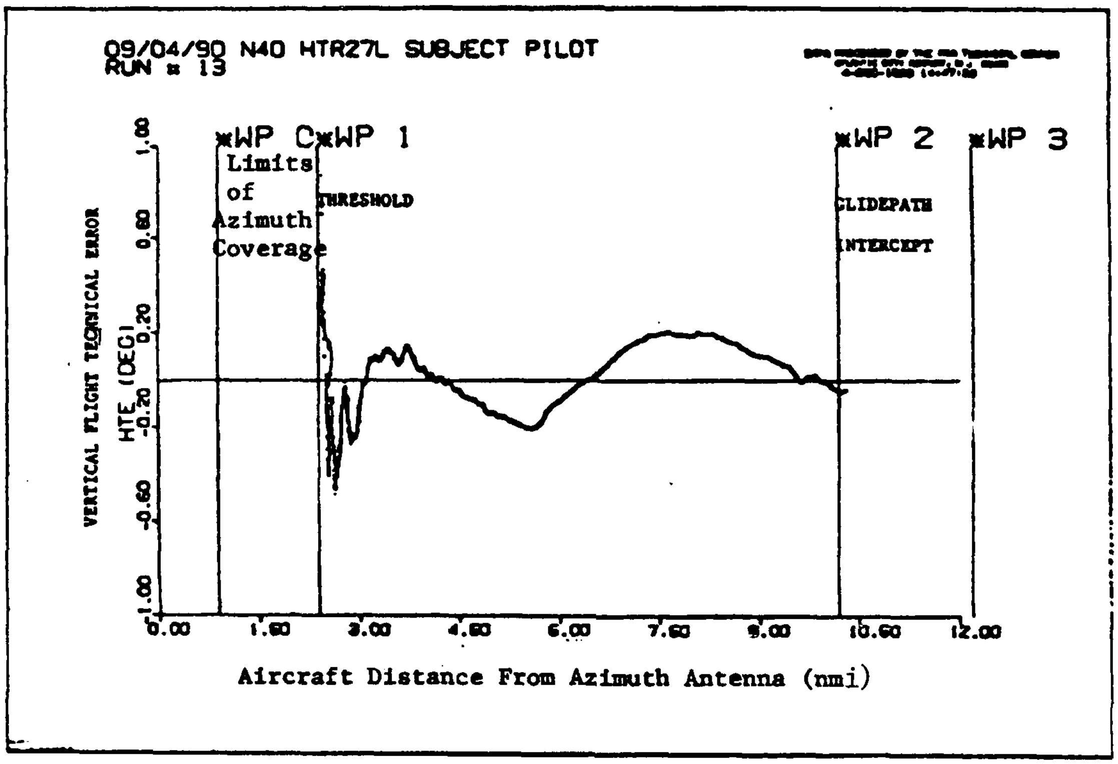

FIGURE 21. VERTICAL FLIGHT TECHNICAL ERROR ON A WIDELY SEPARATED PARALLEL RUNWAY APPROACH

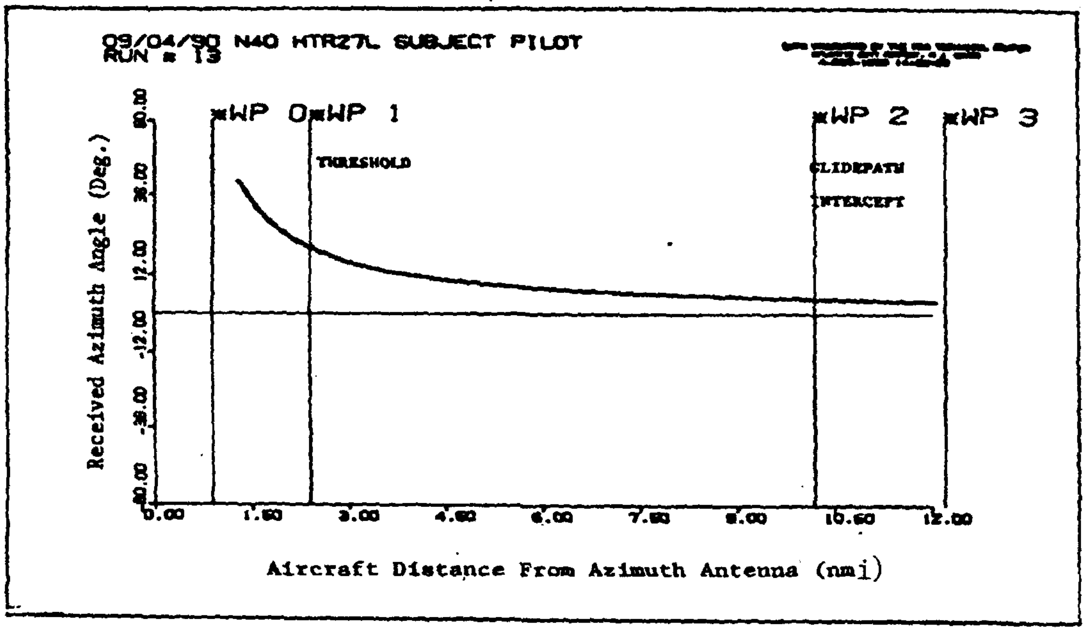

FIGURE 22. RECEIVED RAW AZIMUTH ANGLE ON A RUNWAY 27L APPROACH

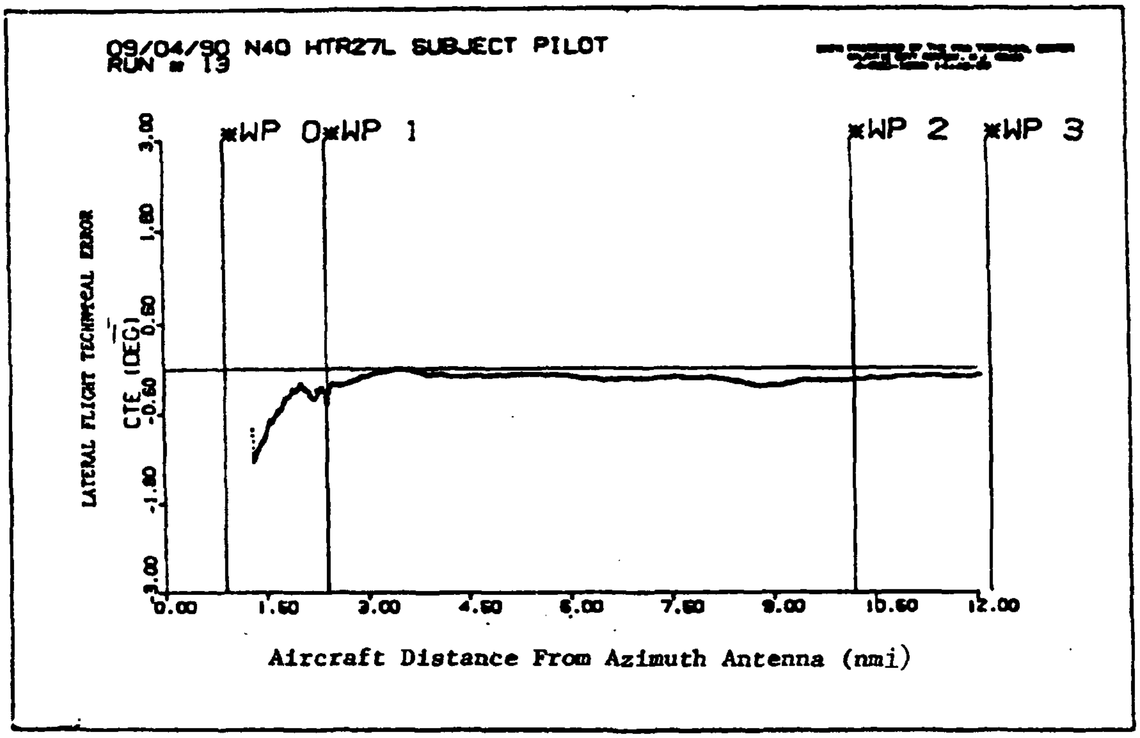

FIGURE 23. LATERAL FLIGHT TECHNICAL ERROR ON A RUNWAY 27L APPROACH

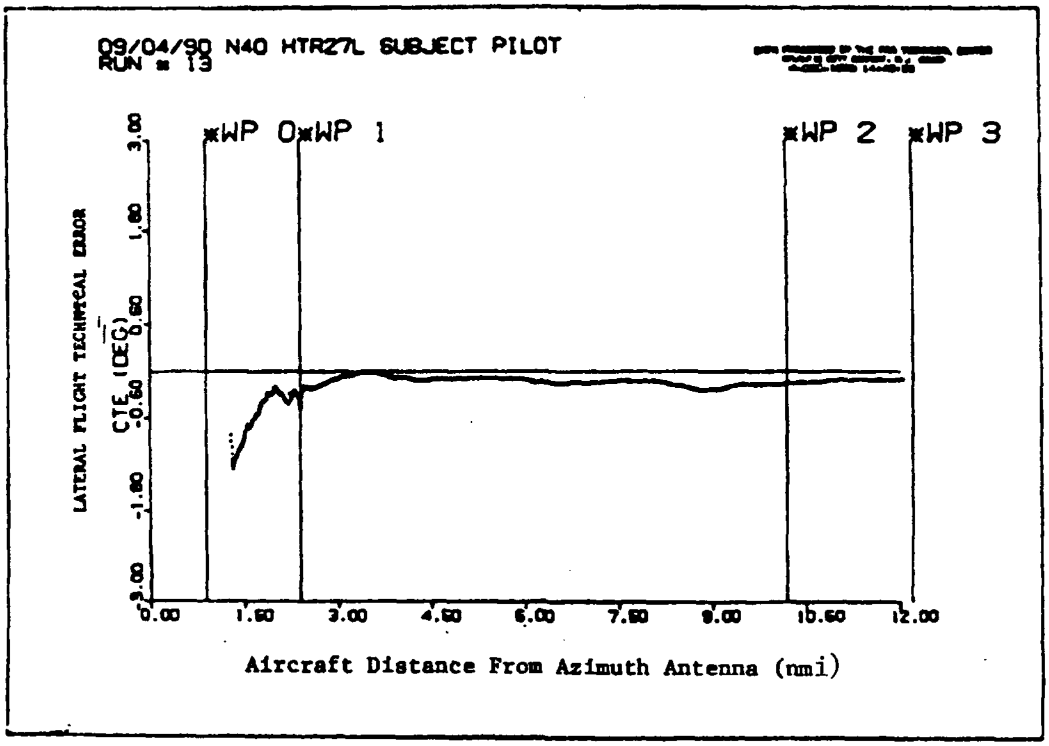

FIGURE 24. MLS RNAV VERTICAL PERFORMANCE FOR AN APPROACH TO A WIDELY SEPARATED SECONDARY PARALLEL RUNWAY

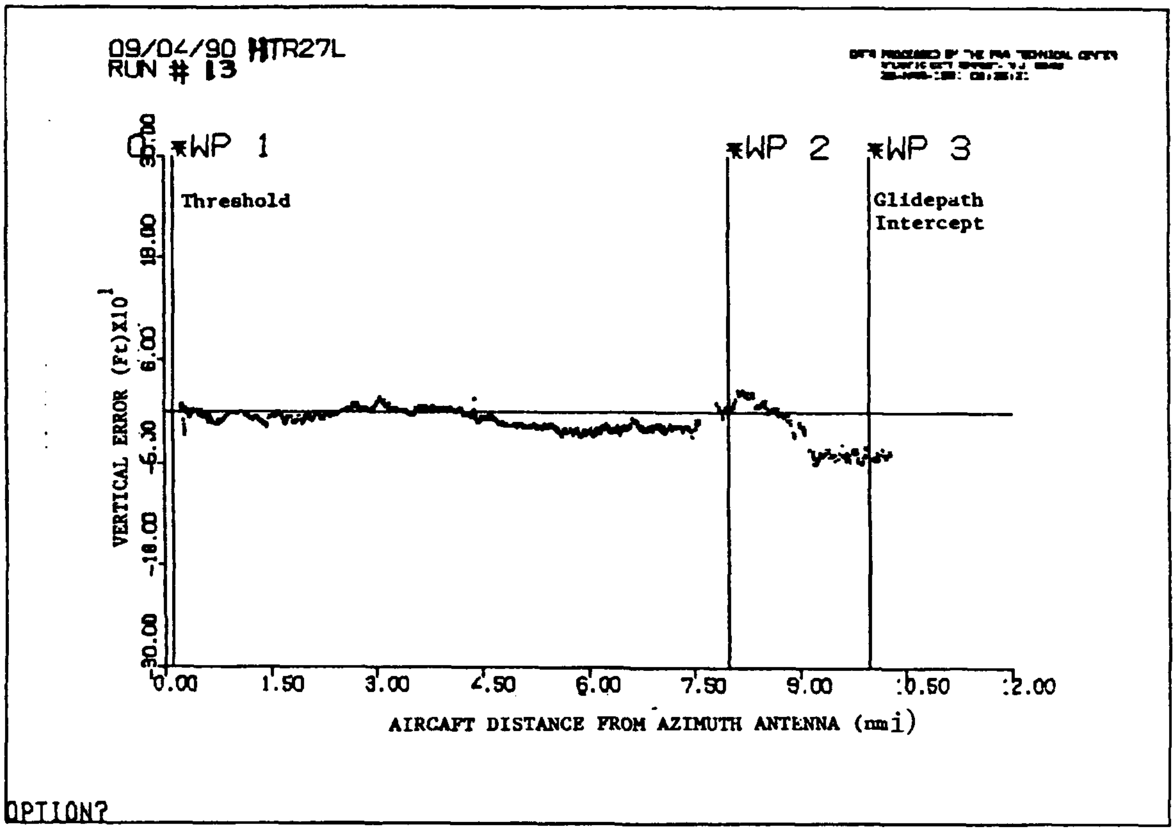

FIGURE 25. VERTICAL ERROR FOR COMPUTED CENTERLINE OPERATION TO A WIDELY SEPARATED PARALLEL RUNWAY

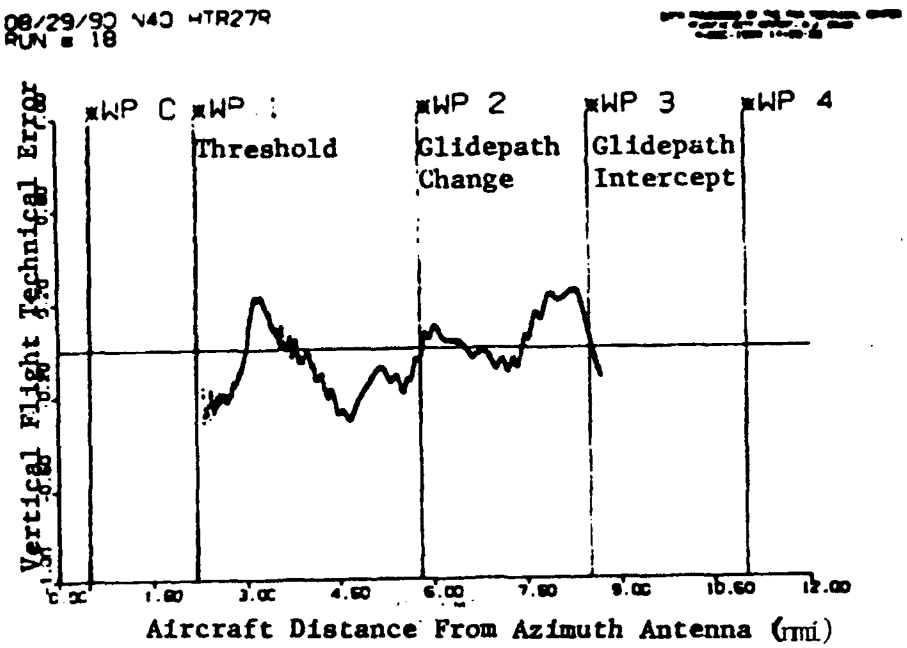

FIGURE 26. VERTICAL TRACKING PERFORMANCE DURING THE GLIDEPATH TRANSITION

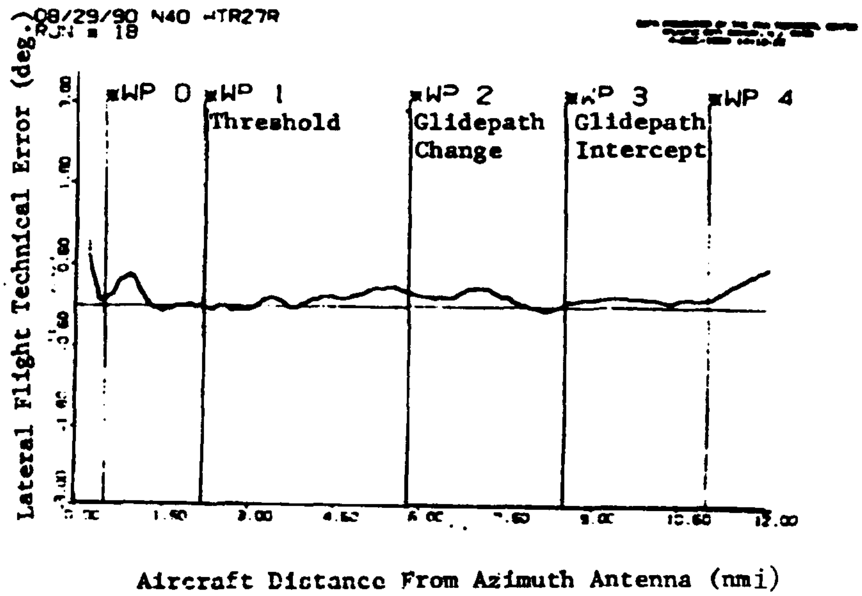

FIGURE 27. LATERAL TRACKING PERFORMANCE DURING THE TWO-SEGMENT GLIDEPATH PROCEDURE

APPENDIX A

AWOP 13 COMPUTED CENTERLINE RECOMMENDATIONS

APPENDIX B

PROPOSED GUIDANCE MATERIAL FOR COMPUTED CENTRE LINE APPROACHES

14. Computed centre line approaches

14.1 General

14.1.1 Computed centre line approaches considered below are based on a computed path along a runway centre line where the azimuth antenna is not sited on the extended runway centre line. The simplest form of a computed centre line approach is one in which the nominal track is parallel to the azimuth zero degree radial. In order to conduct this advanced MLS operation, a greater capability than that available in the basic MLS receiver is required.

Computed centre line approaches to the MLS primary runway are conducted to the runway whose relationship to the MLS ground equipment is identified in the auxiliary data words.

14.1.2 When the final segment is contained in the MLS coverage volume, computed centre line approaches can be conducted along a straight final segment on a descent gradient down to the decision height (DH). Computed centre line approaches may result in decision heights that are above decision heights achievable with aligned MLS approaches.

14.2 Computed centre line approach error budget

14.2.1 Radio Technical Commission for Aeronautics (RTCA) (Note 1) has described a total system error budget for MLS area navigation (RNAV) equipment. This error budget includes contributions due to:

a) ground system performance;
b) airborne sensor performance;
c) ground system geometry effects;
d) MLS RNAV computer computational error; and
e) flight technical error (FTE).

14.2.2 The composite of the above errors with the exclusion of FTE is referred to as total position error. Within 3.7 km (2 NM) of the MLS approach reference datum the permissible total lateral position error for MLS RNAV equipment at a position, 60 m (200 ft) above the MLS datum point on a 3 degree glide path and a runway length of 3 000 m (10 000 ft), is 15 m (50 ft) (Note 2). Similarly, the permissible total vertical position error is 3.6 m (12 ft) at the same position. A portion of the total position error budget has been reserved for the MLS RNAV computer performance (computational error). Within 3.7 km (2 NM) of the MLS approach reference datum, the portion of the error budget

reserved for computational error is 0.6 m (2 ft) both laterally and vertically. The results presented in 14.5 are dependent on meeting this computational accuracy requirement.

14.2.3 Using root sum square methodology the permissible total lateral position error, exclusive of MLS RNAV computer performance is slightly less than 15 m (50 ft). Similarly, the permissible total vertical position error, exclusive of computational error is slightly less than 3.6 m (12 ft). Hence, the combined error due to ground system performance, airborne sensor performance and ground system geometry effects should not exceed 15 m (50 ft) laterally and 3.6 m (12 ft) vertically at the described location. Using this information and assumptions about ground and airborne sensor performance the maximum permissible azimuth and elevation antenna offsets (geometry effects) from the runway centre line can be obtained.

Note 1.- The minimum operational performance standards for airborne MLS area navigation equipment are contained in Document No. RTCA/DO-198.

Note 2.- All errors represent 95 percentile errors.

14.3 Siting and accuracy considerations

14.3.1 Theoretical and operational analysis has shown that several factors will impact the amount of azimuth antenna lateral offset that can be permitted and still obtain lateral and vertical position accuracy identified in 14.2.

14.3.2 Distance between azimuth and elevation antennas

14.3.2.1 For a given azimuth antenna offset, a short azimuth to elevation distance results in relatively large azimuth angles at positions near the approach reference datum. As a result, the error contribution from the DME is large, and the lateral accuracy may degrade unacceptably. At a runway where a large azimuth antenna offset and a short azimuth to elevation distance exist, use of DME/P rather than DME/N may be required to achieve the required lateral accuracy.

14.3.3 Azimuth accuracy

14.3.3.1 The azimuth antenna offset limits obtained in 14.5 are based on the 6 m (20 ft) azimuth path following error accuracy specification (see paragraph 3.11.4.9.4). The use of the recommended 4 m (13.5 ft) azimuth system would permit larger azimuth antenna offsets and still obtain required computed position accuracy at DH. Azimuth angle accuracy is assumed to degrade in accordance with paragraph 3.11.4.9.

14.3.4 DME accuracy

14.3.4.1 Smaller errors in position determination result when DME/P equipment is used and the final approach segment is contained within 5 NM of the MLS approach reference datum. There are two DME/P final approach mode accuracy standards in this region. Resulting azimuth antenna offset values when using

DME/P as presented in 14.5, are based on final approach mode Standard 1 accuracy. Larger azimuth antenna offset values may be permissible if DME/P equipment final approach mode Standard 2 accuracy is used. DME/P final approach mode Standard 1 ranging accuracy is assumed to degrade in accordance with 3.5.3.1.3.4 and Table C. DME/N is assumed to degrade in accordance with 3.5.3.1.3.2

14.3.5 Use of elevation information in the lateral position computation

14.3.5.1 Generally, lateral position computation that excludes elevation information will be sufficient for computed centre line approaches to the primary runway. If elevation information is not used in lateral computation, the lateral error increases. This error increases with azimuth angle, height and decreasing range. Permissible azimuth antenna offsets presented in 14.5 are reduced if elevation information is not used in the lateral computation. Elevation angle accuracy is assumed to degrade in accordance with 3.11.4.9.

14.4 Equipment considerations

14.4.1 Performance of airborne sensors, MLS ground equipment and MLS RNAV avionics implementation influence the range of application of computed centre line approaches. Information presented in 14.5 is based on the following equipment considerations.

14.4.2 Airborne sensors

14.4.2.1 It is assumed the receiver will decode all auxiliary data words required for MLS computed centre line approaches unless the information contained in the data words is available from other avionics sources with the same accuracy and integrity as required for auxiliary data. Digital MLS angle data and range data are needed for computing lateral and vertical provide Angle data quantization is 0.01 degrees. Range quantization is 2m. (0.001 NM).

14.4.3 RNAV Computations

14.4.3.1 No assumption is made about where the RNAV position computations are made. A portion of the computed centre line approach error budget has been reserved for computation error. This should permit flexible algorithm implementation.

14.4.4 Permissible azimuth antenna offset calculation techniques

14.4.4.1 The Radio Technical Commission for Aeronautics (RTCA) has identified several different position determination algorithms (Note 3). Different algorithms can handle different ground equipment configurations. The algorithm designed to handle any ground equipment geometry is the RTCA case 12 algorithm. Permissible antenna offset values were obtained using Monte Carlo simulation techniques. The results were also obtained using a direct analytical method.

The analytical method uses geometric transformations of the maximum MLS angle and range errors to determine system performance. The Monte Carlo technique through the emulation of an MLS RNAV system is a statistical method used to determine system performance.

Note 3.- The minimum operational performance standards for airborne MLS area navigation equipment Document No. RTCA/DO-198 contains position determination algorithm information in Appendix D.

14.4.4.2 Possible restriction in position determination. Depending on ground equipment geometry a region of possible multiple solutions to the position determination algorithm may exist. This region of multiple solutions is dependent on the locations of the elevation antenna and DME transponder relative to the runway and computed approach path. The most pronounced effect occurs when the DME transponder lies in the region between the approach path DH point and the elevation antenna. The position ambiguities can be resolved when the DME transponder is located behind the elevation antenna when viewed from the approach direction. When the DME transponder is located in front of the elevation antenna it may not be possible to resolve the position ambiguity.

14.4.5 Ground equipment geometry

14.4.5.1 The nominal ground equipment geometry in terms of the relative position of the ground components is depicted in Figure 1. The DME/P transponder is assumed to be collocated with the azimuth antenna. When DME/P ground equipment is not available, the DME/N transponder is assumed to be located between the MLS azimuth and elevation antennas.

14.4.5.2 Because of the large error applied to the DME/N, the location of the DME/N transponder has no significant influence on the calculated permissible azimuth antenna offset. This permits DME/N siting over a large area between the azimuth and elevation antennas. Similarly, the offset of the elevation antenna will have little effect.

14.5 Permissible azimuth antenna offset positions for computed centre line approaches to the primary runway

14.5.1 DME results

14.5.1.1 The maximum azimuth offset represents, for a given set of conditions, the largest offset that does not exceed the computed centre line approach error budget identified in 14.2. DME/P results are presented as a function of the azimuth to elevation distance. The permissible azimuth antenna offsets with DME/P are presented in Figure 2.

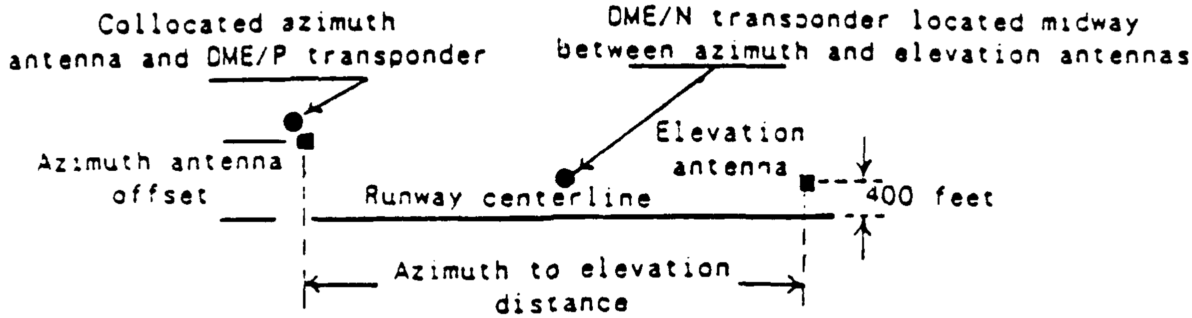

Figure 1: Ground equipment geometry

14.5.1.2 For a given azimuth to elevation distance, the azimuth antenna can be sited any place in the shaded area and the resulting computed centre line approach meet requirements of 14.2.

14.5.1.3 Results were obtained when DME/N ranging accuracies are used. These results are presented in Figure 3.

14.6 Low visibility approaches

14.6.1 Possible applications

14.6.1.1 The possibility of low visibility computed centre line applications may be limited to operations on the primary instrumented runway because of the geometry considerations involved in achieving adequate accuracy. Primary instrumented runway applications where computed centre line capability would be useful are those where the azimuth is offset from the runway centre line due to a severe siting restriction. There may be such azimuth offset applications where low visibility operations would be considered beneficial.

14.6.1.2 The expected airborne implementation for such low visibility computed centre line approaches would use non-computed elevation guidance (assuming the elevation ground antenna is sited normally) and lateral guidance derived from a combination of azimuth (including MLS siting data contained in the basic and auxiliary data functions) and range from the DME/P transponder.

14.6.2 Airborne system performance

14.6.2.1 Safety-critical software associated with the guidance function for non-computed low visibility approaches mainly involves the MLS receiver. For computed centre line approaches, the DME interrogator and the navigation computations must also be considered. The safety-critical software for these functions will have to be designed, developed, documented and evaluated.

14.6.2.2 The necessary algorithms are relatively simple and should not pose any certification difficulty. However, experience with flight management system (FMS) computers indicates that it would be difficult to certify a safety-critical function implemented within an existing FMS. Current FMS architectures are not partitioned to allow separate certification of different functions to different levels of criticality and the size and complexity of an FMS precludes safety-critical certification of the entire FMS computer. Consequently, alternatives to FMS implementation should be considered for computed centre line capability intended for low visibility applications (e.g. incorporation within the autopilot or within the MLS receiver). These alternatives would provide output guidance with the same output characteristics as a normal straight-in approach.

14.6.3 Ground system performance

14.6.3.1 Based on the implementation assumed above in 14.3.5 elevation guidance would be used in exactly the same manner as for basic MLS approaches. Consequently, the elevation ground equipment integrity and continuity of service objectives would remain unchanged from those already given in Table G-4. For lateral guidance, the integrity and continuity of service objectives given in Table G-4 for azimuth would apply to the azimuth and DME combined, resulting in objectives for both that are more stringent than those needed for basic MLS operations. However, a low visibility computed centre line operation to a 100 ft DH may be achieved by the use of ground equipment meeting the level 4 objectives contained in Table G-4.

14.7 Computed centre line approaches to parallel secondary runways

14.7.1 A secondary runway as defined here is a runway that has a different geometric relationship than the one contained in the auxiliary data A words. Computed centre line approaches to a parallel secondary runway are approaches along a computed path on the extended runway centre line which is not aligned with an MLS azimuth radial and/or elevation angle but is parallel to the primary runway centre line.

14.7.2 The material in this section provides guidance on permissible runway geometries for computed centre line approaches to a parallel secondary runway to DH's of 60 m (200 ft). The material in this section is based on the theoretical application of MLS and DME/P (Standard 1) SARPs. The error budget used is the conservative error budget identified in 14.2, although relaxations of this error budget are described in 14.7.6.1.

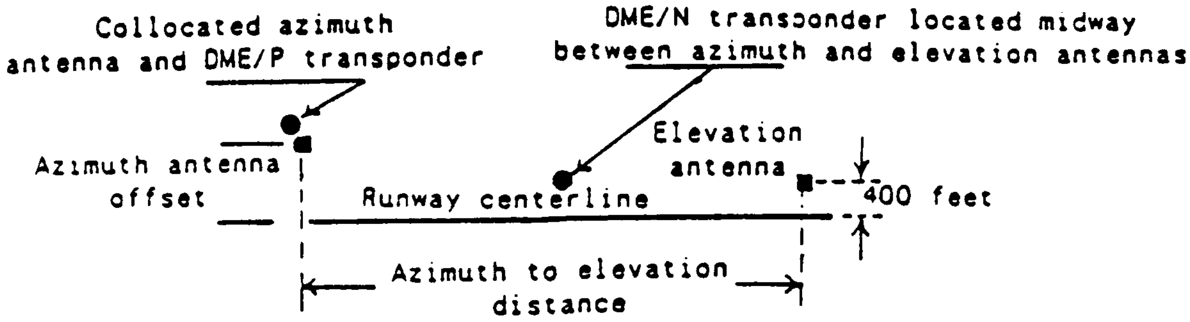

Figure 1: Ground equipment geometry

14.5.1.2 For a given azimuth to elevation distance, the azimuth antenna can be sited any place in the shaded area and the resulting computed centre line approach meet requirements of 14.2.

14.5.1.3 Results were obtained when DME/N ranging accuracies are used. These results are presented in Figure 3.

14.6 Low visibility approaches

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14.6.1.1 The possibility of low visibility computed centre line applications may be limited to operations on the primary instrumented runway because of the geometry considerations involved in achieving adequate accuracy. Primary instrumented runway applications where computed centre line capability would be useful are those where the azimuth is offset from the runway centre line due to a severe siting restriction. There may be such azimuth offset applications where low visibility operations would be considered beneficial.

14.6.1.2 The expected airborne implementation for such low visibility computed centre line approaches would use non-computed elevation guidance (assuming the elevation ground antenna is sited normally) and lateral guidance derived from a combination of azimuth (including MLS siting data contained in the basic and auxiliary data functions) and range from the DME/P transponder.

14.6.2 Airborne system performance

14.6.2.1 Safety-critical software associated with the guidance function for non-computed low visibility approaches mainly involves the MLS receiver. For computed centre line approaches, the DME interrogator and the navigation computations must also be considered. The safety-critical software for these functions will have to be designed, developed, documented and evaluated.

14.6.2.2 The necessary algorithms are relatively simple and should not pose any certification difficulty. However, experience with flight management system (FMS) computers indicates that it would be difficult to certify a safety-critical function implemented within an existing FMS. Current FMS architectures are not partitioned to allow separate certification of different functions to different levels of criticality and the size and complexity of an FMS precludes safety-critical certification of the entire FMS computer. Consequently, alternatives to FMS implementation should be considered for computed centre line capability intended for low visibility applications (e.g. incorporation within the autopilot or within the MLS receiver). These alternatives would provide output guidance with the same output characteristics as a normal straight-in approach.

14.6.3 Ground system performance

14.6.3.1 Based on the implementation assumed above in 14.3.5 elevation guidance would be used in exactly the same manner as for basic MLS approaches. Consequently, the elevation ground equipment integrity and continuity of service objectives would remain unchanged from those already given in Table G-4. For lateral guidance, the integrity and continuity of service objectives given in Table G-4 for azimuth would apply to the azimuth and DME combined, resulting in objectives for both that are more stringent than those needed for basic MLS operations. However, a low visibility computed centre line operation to a 100 ft DH may be achieved by the use of ground equipment meeting the level 4 objectives contained in Table G-4.

14.7 Computed centre line approaches to parallel secondary runways

14.7.1 A secondary runway as defined here is a runway that has a different geometric relationship than the one contained in the auxiliary data A words. Computed centre line approaches to a parallel secondary runway are approaches along a computed path on the extended runway centre line which is not aligned with an MLS azimuth radial and/or elevation angle but is parallel to the primary runway centre line.

14.7.2 The material in this section provides guidance on permissible runway geometries for computed centre line approaches to a parallel secondary runway to DH's of 60 m (200 ft). The material in this section is based on the theoretical application of MLS and DME/P (Standard 1) SARPs. The error budget used is the conservative error budget identified in 14.2, although relaxations of this error budget are described in 14.7.6.1.

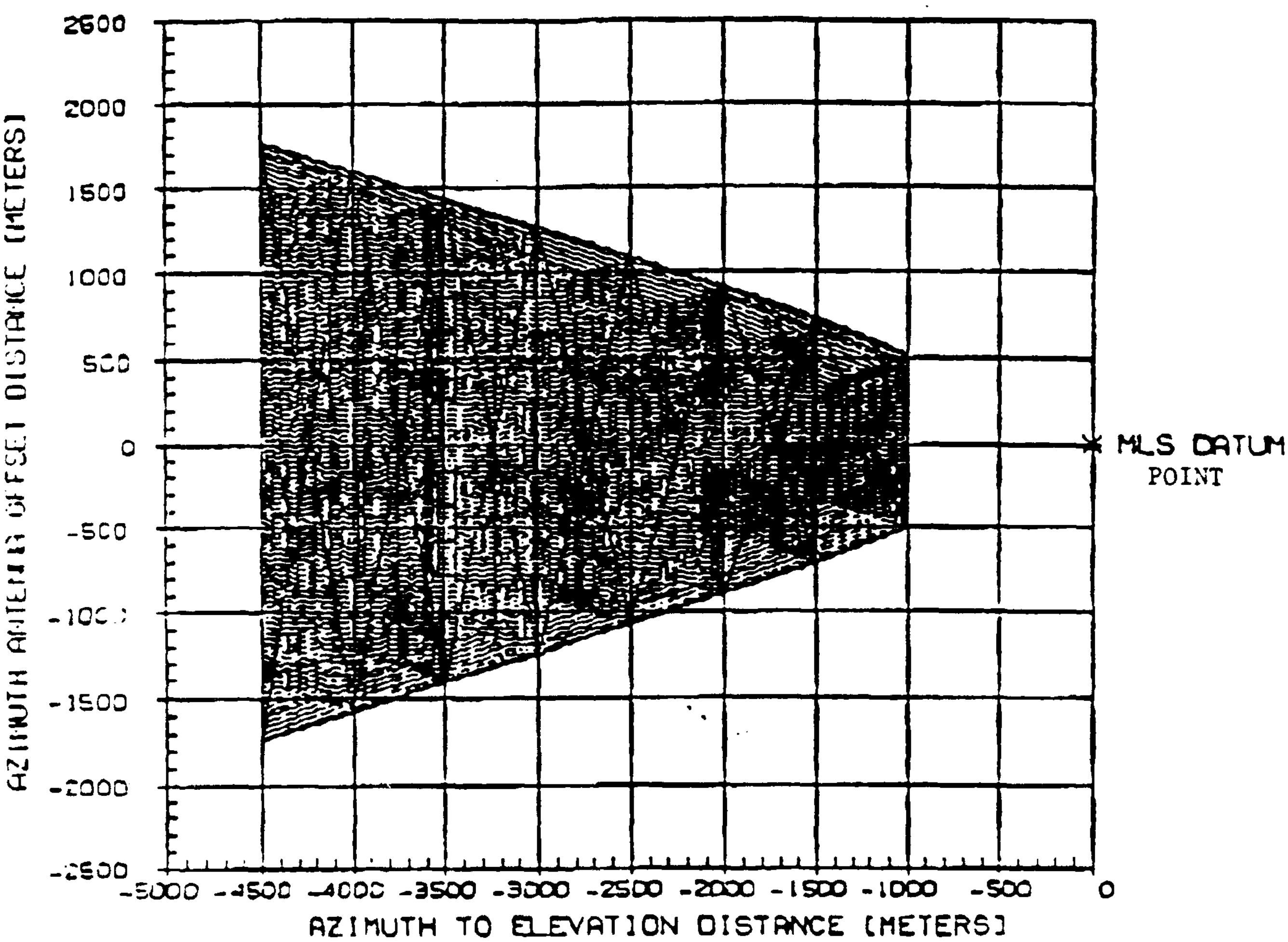


Figure 2. Permissible azimuth antenna offsets with DME/P (Standard 1) ranging

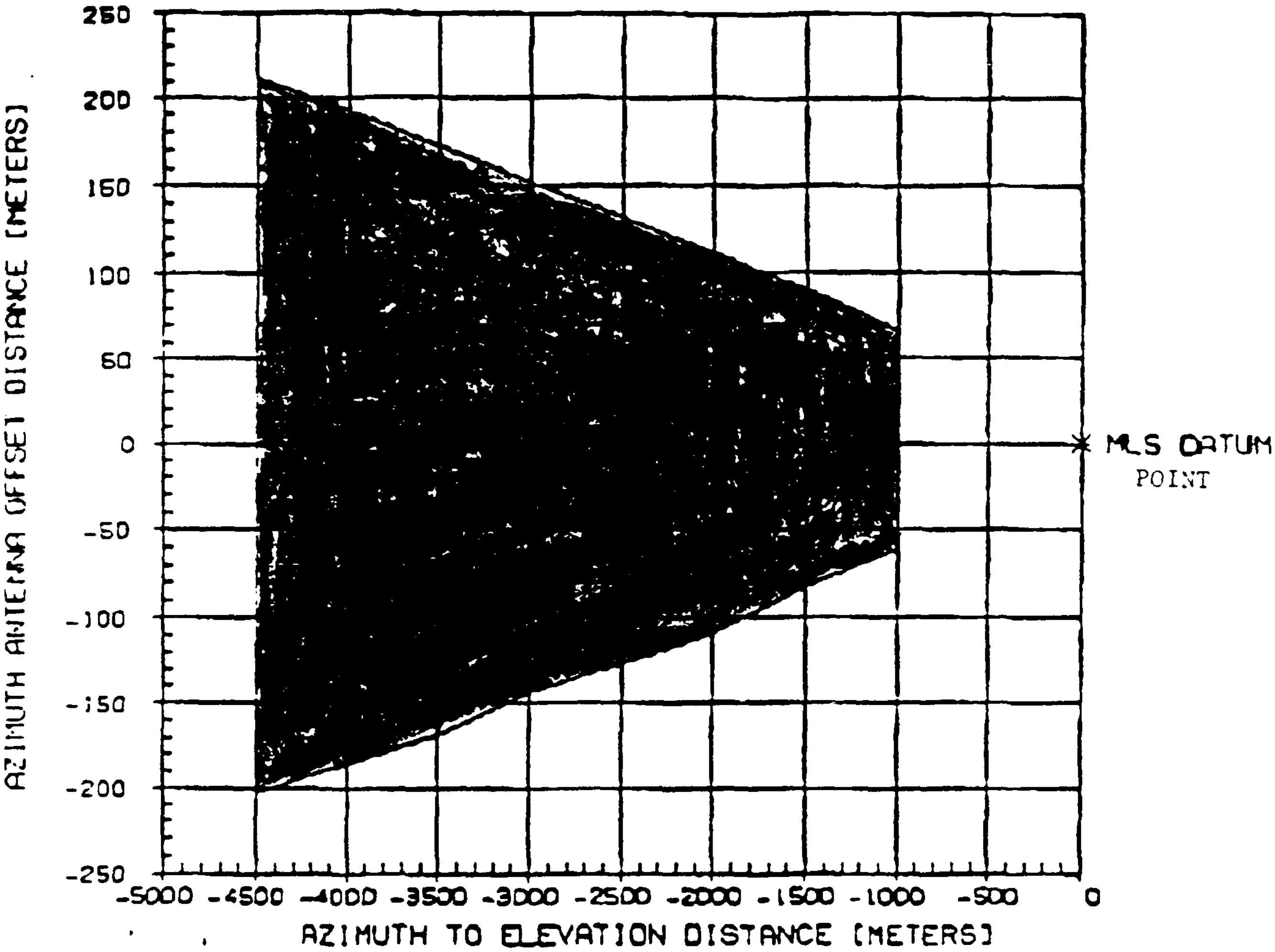


Figure 3. Permissible azimuth antenna offsets with DME/N ranging

14.7.3 Runway geometry considerations

14.7.3.1 Figure 4 presents the runway and equipment geometry. The secondary runway location is established laterally with the use of runway separation in metres. Negative values represent secondary runway locations left of the primary runway. The longitudinal position of the secondary runway threshold is referred to as threshold stagger relative to the primary runway. Negative values represent threshold stagger forward of the primary runway threshold.

14.7.4 Large runway separation considerations

14.7.4.1 Additional considerations are necessary for computed centre line approaches to widely spaced parallel runways. These considerations include:

a) adequate signal coverage to DH for some parallel runway geometries may require the use of an elevation antenna with more than ±40 degrees of horizontal coverage;

b) the critical areas around the MLS antennas may have to be increased for these operations;

c) these operations require the use of elevation guidance below the primary runway minimum glide path.

14.7.5 Runway geometry for computed centre line approaches

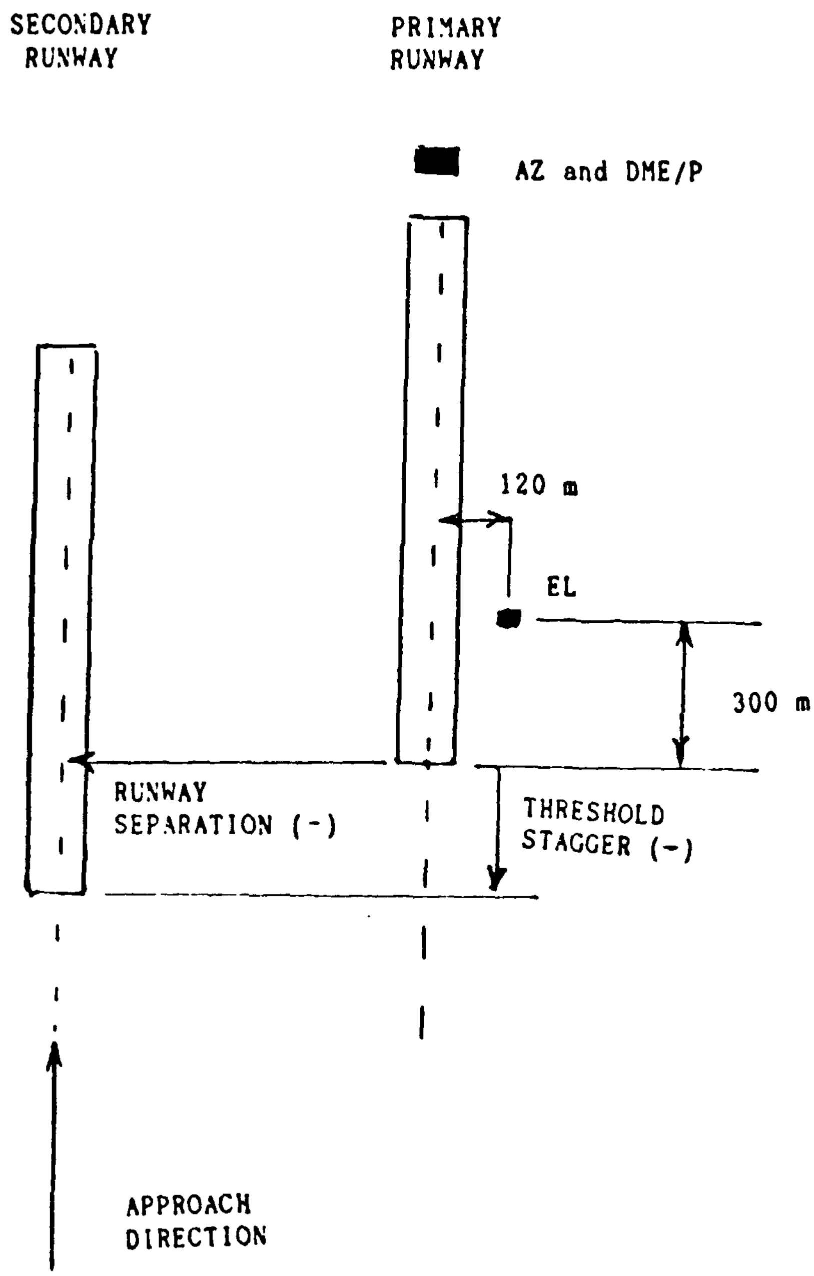
14.7.5.1 Figure 5 shows permitted runway separations and threshold staggers for the secondary runway. It represents results for a 3 000 m (10 000 ft) primary runway. The geometrics change marginally with primary runway length. The shaded area represents results obtained using existing MLS and DME/P (Standard 1) SARPs and the error budget identified in 14.2. To use Figure 5, enter the values for secondary runway separation and threshold stagger. If the resulting point lies within the shaded area a computed centre line approach to a 200 ft DH on a 3 degree glide path is possible.

Note.- The circular region near the 1 200 m runway stagger is due to the upper limit of elevation guidance used. This region is not expected to present any practical operational limitations.

14.7.6 Extensions to the runway geometries

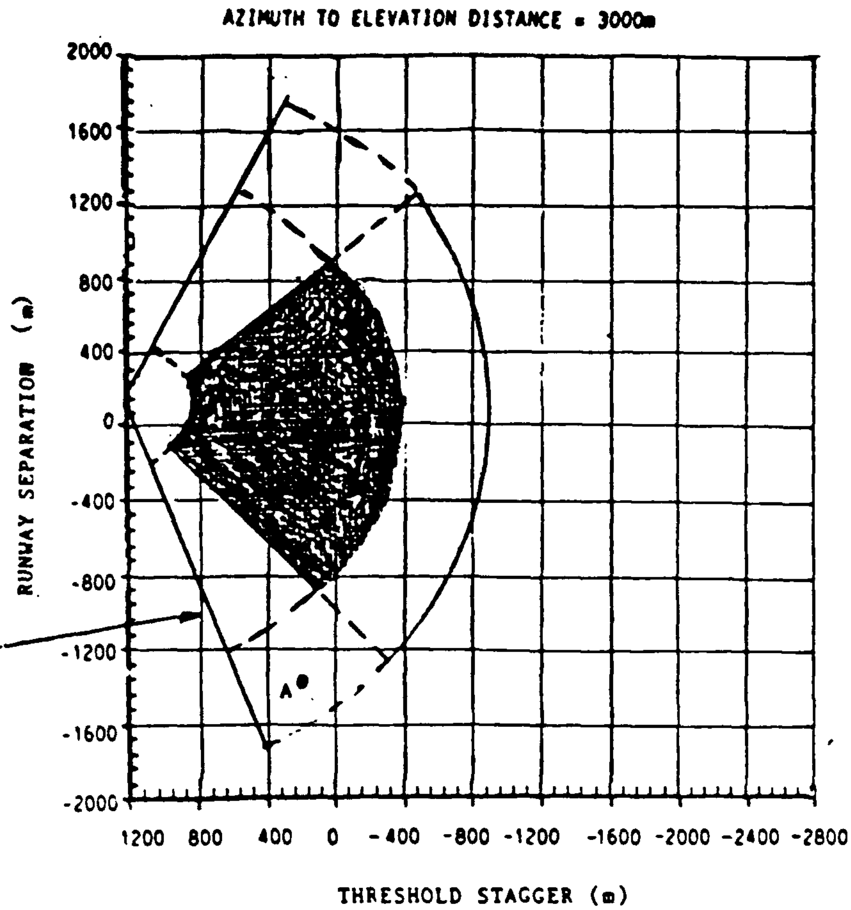
14.7.6.1 Flight and ground tests have shown that the shaded area can be expanded with the following additional considerations:

a) an angular expansion is possible by utilizing existing elevation guidance outside the minimum specified azimuth proportional guidance sector. Elevation guidance for this angular expansion must be verified; and



Note.- The position shown for the elevation antenna is defined by typical values that are used to compute the data shown in Figure 5.

Figure 4. Runway and equipment geometry



Note 1.- This boundary is dependant on elevation antenna performance

Note 2.- Point A represents the example described in 14.7.3.1.

Figure 5. Permissible runway geometries for computed centre line operations to parallel secondary runways

b) a radial expansion is possible with a slight relaxation of the vertical error budget to 4.9 m (16 ft). This relaxation is still very conservative and equates to 66 per cent of the equivalent ILS error budget [7 m (24.1 ft)].

14.7.6.2 An example of the use of Figure 5 is presented by point A. By using these extensions a computed centre line approach to a secondary runway is possible for a -1 400 m runway separation and 200 m threshold stagger.

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APPENDIX B

CARDIFF SUBJECT PILOT QUESTIONNAIRE RESULTS

PILOT QUESTIONNAIRE
CARDIFF/HEATHROW MLS RNAV DEMONSTRATION
SEPTEMBER 4-5, 1990

Pilot #	Total Flight Hours	Time in B-727	Pilot Certificates
1	5,600	NIL	RAF
2	4,100	NIL	UK ATPLITEST Pilot
3	15,000	NIL	UK ATPL USA ATR
4	15,000	1000	ATP B-727
5	11,000	NIL	UK ATPL
6	4,SW	300	ATP
7	13,600	600	ATPL CAA Examiner Authorities
8	9,000	NIL	ATP (737)
9	7,000	NIL	Commercial P.L.
10	11,000	6,000	ATPL TREIIRE
11	3,500	NIL	ATPL
12	3,000	16 MIN	TEST Pilot (Military RAF)
13	9,500	NIL	UK ATPL US CPLIIR

DEPARTURES

QUESTION 1: When compared with a standard instrument departure how would you rate the pilot workload for the MU RNAV departures you flew?

Pilot #	Much Less	Slightly Less	About the Same	Slightly More	Much More
1				X	
2			X		
3				X	
4			X		
5			X		
6					
7			X		
8			X		
9		X			
10			X		
11					
12		X			
13					

COMMENTS:
PILOT #

2 Based on equivalent instrument standard and appropriate NAVAIDS.

6 It varies depending on what it is compared to e.g., compared to the 747-400 there are more switch selections and the overall effect is to make it a slightly higher workload task. Compared to old electro-mechanical display aircraft, the computed flightpath and the reduction of switch selection required makes the workload slightly

less, but, nevertheless, a worthwhile reduction in load. The coverage offered by MLS, i.e., +/-40 degrees and 10 nmi is very restrictive.

12. Equivalent to an FMS managed departure.

QUESTION 2: What difficulty, if any, did you experience with the MLS RNAV departure?

Pilot #

1 Only difficulty was associated with aircraft flight director not the MLS system.

2 Lateral tracking sensitivity, because of the effect of a strong x-wind appeared too great. The FD was not optimized to cater for this.

3 Too much monitoring of CDU required (I fly 737-300 EFIS).

4 None other than the known limitations of the aircrafts flt. dir.

5 None

6 Excess speed meant going outside the computed turn.

7 No difficulty with what was required but the flight director commands made it difficult to fly really accurately.

8 Comment: In the event of an engine failure requiring an acceleration at say 1000 feet, (to clean) at that higher speed it would be difficult to follow.

9 It was really difficult to judge sitting at the controls only 2 minutes. So getting accustomed to what was going on was real difficult. Overshot altitude so guidance should be in both vertical and horizontal plane.

10 Obviously the CDU information will be better placed on later a/c models. Perhaps H.U.D. display? or tied into flight director? or both?

11 Mainly unfamiliarity with a/c. If familiar little otherwise.

12 None the system was easy to follow and the lateral error displayed on the deviation display on the MSI enabled qualitative assessment of lateral error to be easily made.

APPROACHES

QUESTION 1: How would you rate your workload on the MLS advanced approaches at Cardiff when compared with a nonprecision approach?

Pilot #	Much Less	Slightly Less	About the Same	Slightly More	Much More
1		X			
2					
3		X			
4		X			
5				X	
6		X			
7		X			
8		X			
9					
10		X			
11					X
12	X				

COMMENTS:

PILOT #

2 S-turn approaches no comparison.

11 Mainly unfamiliarity with a/c. If familiar little otherwise.

12 Much less than a nonprecision app. Similar to a good FD ILS.

QUESTION 2: What difficulty, if any, did you experience with the MLS approach procedures at Cardiff?

PILOT #

1 The approach was flown in a strong crosswind in the sector between the 2 turns and as the configuration is not track based you are always behind the wind - with a fully integrated system the problem wouldn't exist and the workload would be significantly less.

2 The wind effect caused the x-wind sections to be difficult. The HSI deviation could not be adequately interpreted during turns and short x-wind legs - poor FD did not assist.

3 Sluggish flight director.

4 Same as above

5 None other than anticipating the very short dog leg onto final.

6 The FD is very poor and worthwhile performance required use of the raw data. This put the workload up significantly. Ignoring the remark above for a moment, the overall effect was to reduce the workload somewhat.

7 Only criticism again regarding flt director commands. I understood and was not disoriented at all by presentation.

8 Nil significant problem.

9

10 With excellent instruction - no problem!!!

11 As 2 DEP

12 No difficulty in flying.

13 n/a

QUESTION 3: State your overall impressions of the advanced procedures you were exposed to during the demonstration.

PILOT #

1 They are entirely feasible and with a modem flt director system would be no more difficult to fly than a normal precision ILS.

2 Procedure performance of MLS were probably satis. but inadequate displays in 727 and poor fd performance in strong winds did not produce required CAT I standard driving s-turn procedure. Glide-path deviation indication being nil on approach to flightpath change gave no anticipation.

3 It would be nice to see a demonstration using a modem a/c equipped with EFIS MAP ETL

4 Very impressive and relatively easy tracking task. Suggest time and dist. to way point tabular info be made much more prominent - perhaps on a separate alpha-numeric display directly in pilot's view.

5 The profiles were fairly easy to follow only problems were self induced by unfamiliarity with a/c. Also it took some time to include RNAV display often enough in basic instrument scan.

6 Once set up, the MLS is essentially transparent to the pilot and that's good. The curved approaches and departures were all good. Straightforward, allowing for standard if the flight test displays, for airline use, the CDU would need to be markedly changed.

7 The procedures themselves were not difficult but a more advanced presentation could provide less switching and more positive LOC G.P. info.

8 To be smooth it is necessary to be "in front" of the flight director in the turnsthis is no problem.

9 Very favorable - needs adaptation of cockpit procedures, crew coordination. FD could be improved in particular on MLS procedures (ok for normal flying).

10 In long term I see no problems that are not insurmountable, e.g., - many pilots are used to checking ILS against outer marker or an ADF (although time's now coming into greater usage).
- probably most airlines would provide hands on training in simulators. That'll provide some business for somebody.

11 Good but initial impression only.

12 The FD, HSI combination enabled the CDF12D and CDF30B approaches to be easily flown. An EFIS display would have greatly enhanced the situational awareness especially during the intercept phase.

Question 1: How would you rate the workload on the 27L approach when compared with an ILS approach?

Pilot #	Much More	Slightly More	About the Same	Less	Much Less
1			X		
2			X		
3			X		
4				X	
5			X		

Comments:

Pilot 1: Very impressive

Pilot 2: The current display provided a poor indication of approaching glide slope. The goal should be to have indications similar to the current ILS.

Pilot 3: Display information of Glideslope intercept is lacking. I thought the 27L procedure was quite remarkable with a very stable glideslope indication to below 70 feet and a stable LOC (sic: lateral guidance) signal at least 2/3 the way down the runway.

Question 2: What difficufty if any did you experience with the two segment glidepath (27R approach) at Heathrow?

Pilot 1: None

Pilot 2: None

Pilot 3: The transition was easy at Waypoint 2. No problem.

Pilot 4: No problem

Pilot 5: I was surprised how easy and precise it could be flown. Transition could be at a lower altitude.

Question 3: State your overall impressions of the advanced procedures you were exposed to during the demonstration.

Pilot 1: They are entirely feasible and with a modern flight director system would be no more difficult to fly than a normal precision ILS.

Pilot 2: Very impressive and relatively easy tracking task. Suggest time and dist. to waypoint tabular information be made much more prominent - perhaps alpha-numeric display in the pilot's view.

Pilot 3: The profiles were fairly easy to follow. Only problems were self induced by unfamiliarity with a/c. Also, it took some time to include RNAV display often enough in basic instrument scan.

Pilot 4: The procedures themselves were not difficult but a more advanced presentation could provide less switching and more positive LOC GP information.

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